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# THESIS

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AN INTERACTIVE COMPUTER CODE FOR  
PRELIMINARY DESIGN  
OF SOLID PROPELLANT ROCKET MOTORS

by

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An Interactive Computer Code for Preliminary Design  
of Solid Propellant Rocket Motors

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## ABSTRACT

An interactive computer code for the preliminary design of solid propellant rocket motors ("SPRMD") was successfully developed and its use was demonstrated through a design example. "SPRMD" was written in FORTRAN for use on an IBM PC/AT. It combined several existing codes ("MICROPEP", "GRAINS", "ROCKET", etc.) and used the performance loss estimation methods suggested by the AGARD Propulsion and Energetics Panel for aluminized propellants.

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# TABLE OF CONTENTS

	PAGE
I. INTRODUCTION .....	10
A. BACKGROUND .....	10
B. OBJECTIVES .....	12
C. APPROACH .....	12
II. SOLID PROPELLANT ROCKET MOTOR DESIGN PROCESS .....	14
A. GENERAL .....	14
B. INPUTS .....	14
C. PROPELLANT SELECTION .....	18
D. THEORETICAL PERFORMANCE COMPUTATION .....	18
E. NOZZLE GEOMETRY AND MATERIAL SELECTION .....	19
F. PERFORMANCE LOSS ESTIMATION .....	19
G. THROAT AND EXIT AREA .....	20
H. GRAIN DESIGN .....	23
I. THRUST AND PRESSURE VERSUS TIME CALCULATION...	25
J. TERMINAL VELOCITY AND RANGE CALCULATION .....	27
III. "MICRÓPEP" .....	28
A. BASIC ASSUMPTIONS .....	28
B. INPUTS .....	29
C. OUTPUTS .....	29



IV.	LOSS MECHANISMS .....	30
	A. THRUST COEFFICIENT EFFICIENCY .....	30
	B. COMBUSTION EFFICIENCY .....	33
	C. PROGRAM .....	34
V.	"GRAINS" .....	35
	A. "DESIGN MODE" .....	35
	B. "BURNBACK MODE" .....	37
	C. COMMENTS ON PROGRAM OPERATION .....	37
VI.	"ROCKET" .....	38
	A. BASIC ASSUMPTIONS .....	38
	B. ANALYTICAL BACKGROUND .....	39
	C. INPUTS .....	39
	D. OUTPUTS .....	40
VII.	"FLYIT" .....	42
VIII.	COMBINED PROGRAM .....	43
	A. ALGORITHM .....	43
	B. BRANCHING .....	46
IX.	EXAMPLE OF DESIGN PROGRAM .....	47
X.	CONCLUSIONS AND RECOMMENDATIONS .....	67
	A. CONCLUSIONS .....	67
	B. RECOMMENDATIONS .....	67

APPENDIX .....	69
REFERENCES .....	90
INITIAL DISTRIBUTION LIST .....	91



## TABLES

1. INPUT PARAMETERS
2. MICROPEP OUTPUT FOR  $P_c = 250$  AND 1030 PSIA:  
 $P_e = 10.1$  PSIA 78% AP, 12% HTPB, 10% Al
3. ESTIMATED PERFORMANCE LOSSES
4. CALCULATED MOTOR DATA
5. REQUIRED PARAMETERS FOR SELECTED WEBS
6. OUTPUT FROM "DESIGN MODE" OF "GRAINS"
7. GRAINS "BURNBACK" OUTPUT FOR CASE II
8. INPUT DATA FOR "ROCKET", CASE II
9. SAMPLE OUTPUT FROM "ROCKET", CASE II
10. SUMMARY OF RESULTS FOR THREE GRAIN DESIGNS  
 $D = 16.0$  IN,  $L = 40$  IN

## FIGURES

1. DESIGN PROCESS
2. TYPICAL PRESSURE OR THRUST VERSUS TIME PROFILES
3. EFFECT OF RESIDENCE TIME ON  $I_{sp}$  EFFICIENCY FOR AN Al-PBAN PROPELLANT (FROM REF. 2)
4. MASS CONSERVATION IN A SOLID PROPELLANT MOTOR
5. NOMENCLATURE FOR "GRAINS" DESIGN MODE
6. FLOW CHART FOR THE COMBINED PROGRAM
7. PRESSURE-TIME PROFILES FROM "ROCKET"

## I. INTRODUCTION

### A. BACKGROUND

Solid propellant rocket motor design is a very complex process which often requires many iterations in order to accomplish a successful design. Usually, the first step in the design process is to obtain accurate input data on missile system restraints. Examples of these restraints are ballistic requirements (which can include thrust, burning time, total impulse) and mission/vehicle requirements (which can include motor length, diameter, allowed hazard and plume properties, altitude, etc.). These parameters are often referred to as independent parameters. Through the use of these independent parameters, the required propellant burn time and properties can be roughly estimated. Then, theoretical motor performance and losses can be estimated. The thrust-time requirements together with the expected structural loads permit initial selection of a grain design.

The next step of solid propellant rocket motor design is to use the propellant properties and grain design to predict the pressure- and thrust-time profiles and the total impulse of the motor. Propellant properties and grain design are then iterated until these independent variable requirements are met, together with acceptable propellant stress levels. A final step in the missile design process is to use the

thrust-time profile in an external aerodynamics code to ensure that range and terminal velocity requirements are met.

During the past decade, there has been significant progress in the automation of solid rocket motor design. It is mainly because of the extensive use of digital computers, which greatly facilitate the iterative type computations mentioned above (Ref. 1). In recent years, many of the design processes have been accomplished using separate computer codes, i.e., adiabatic equilibrium combustion codes, codes which estimate performance losses, grain geometry optimization codes, etc. These codes have, in some cases, been combined into much larger design codes, and they are often difficult and expensive to run. Recently, PC versions of some rocket motor design codes have become available. However, they must still be used individually, and were not all available for use on the same computer. The use of these codes was also very inconvenient in that the same parameters often had different variable names in the various codes. The user had to transfer or convert the data from one code to the next.

In addition, a recent AGARD publication has provided recommended empirical equations which can be used for rapid and accurate estimation of performance losses for aluminized propellants.

## B. OBJECTIVES

The first objective was to outline a suitable "Solid Propellant Rocket Motor Preliminary Design Procedure" which, of course, is not a unique procedure. The second objective was to create, modify, and/or combine the PC versions of the necessary design codes into one interactive code which could be conveniently used for preliminary design on an IBM PC/AT microcomputer. The final objective was to demonstrate the program by designing a tactical solid propellant rocket motor combustor.

## C. APPROACH

The approach to achieve the objectives was first to detail an acceptable preliminary design process. The algorithm of the design process was then followed, utilizing several existing codes and loss estimation methods as appropriate, to obtain an integrated design code for use on the IBM PC/AT. The programs to be used were (1) "MICROPEP" (a microcomputer version of a propellant evaluation program from China Lake, Naval Weapons Center), which calculates the adiabatic, equilibrium combustion process, and theoretical motor performance; (2) "GRAINS" (a radial spoked star grain design program from CSD); (3) "ROCKET" (a Lockheed internal ballistics program), which is a one-dimensional flow code which predicts pressure and thrust versus time; and (4) "FLYIT" (a flight simulation program from China Lake, Naval

Weapons Center), which performs simplified trajectory calculations. In addition, a code based upon AGARD-AR-230 was written for estimation of performance losses for aluminized propellants. Capabilities of the final program were then to be demonstrated by considering the design of a tactical motor.



## II. SOLID PROPELLANT ROCKET MOTOR DESIGN PROCESS

### A. GENERAL

The method of solid rocket motor design adopted in this work is shown in Figure 1. It was assumed that the required information on fundamental propellant properties (burning rates, temperature sensitivity, etc.) was known. In addition, the design process discussed herein did not include any stress analysis for the propellant grain or case.

### B. INPUTS

The inputs that are required to satisfy mission objectives (the independent parameters) were as follows:

#### 1. Ballistics Performance Requirements

- a. Average thrust ( $\bar{F}$ ) or thrust-time profiles,
- b. Burn time ( $t_b$ ), or
- c. Total impulse ( $I_t$ ).

These parameters are interrelated as shown in

Figure 2. Thus 
$$I_t = \int_0^{t_b} F dt \quad (2.1)$$

$$\bar{F} = I_t / t_b \quad (2.2)$$

#### 2. Mission/Vehicle Constraints

These requirements are directly related to the motor design and include:



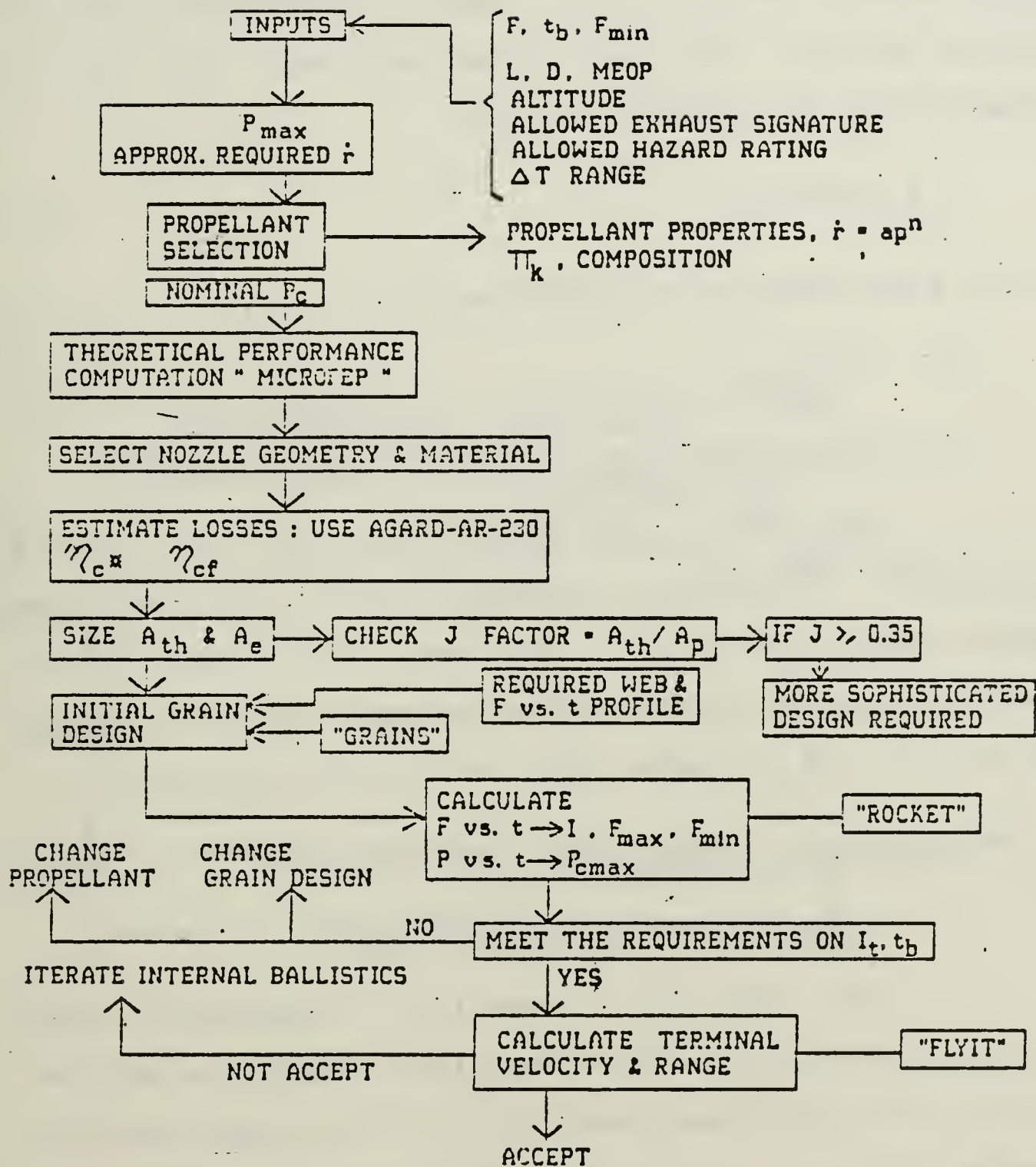


FIGURE 1.  
DESIGN PROCESS

a. Envelope

The allowable envelope (motor length  $L$ , motor inside diameter  $D$ ) is the fundamental constraint on the motor geometry, which can be used to estimate the required burning rate ( $r$ ) and total volume available ( $V_a$ ) for the propellant by following relations:

$$\dot{r} \cong (D/4)/t_b \quad (2.3)$$

(i.e., a web fraction of approximately .5)

$$V_a = (\pi D^2/4) L \quad (2.4)$$

b. Maximum Expected Operating Pressure (MEOP)

The MEOP is set by the structural limit of the motor case. The maximum operating pressure at maximum propellant temperature ( $P_{maxtp}$ ) is less than the MEOP by the factor of reproducibility tolerance (see Figure 2).  $P_{maxtp}$  can be initially estimated from the following equation

$$P_{maxtp} = \text{MEOP} (1 - \text{reproducibility tolerance}) \quad (2.5)$$

c. Temperature Range and Altitude

The operating propellant temperature range effects the selection of the propellant through the required burning rate temperature sensitivity. The design altitude, together with the nominal chamber pressure determine the exhaust nozzle area ratio.

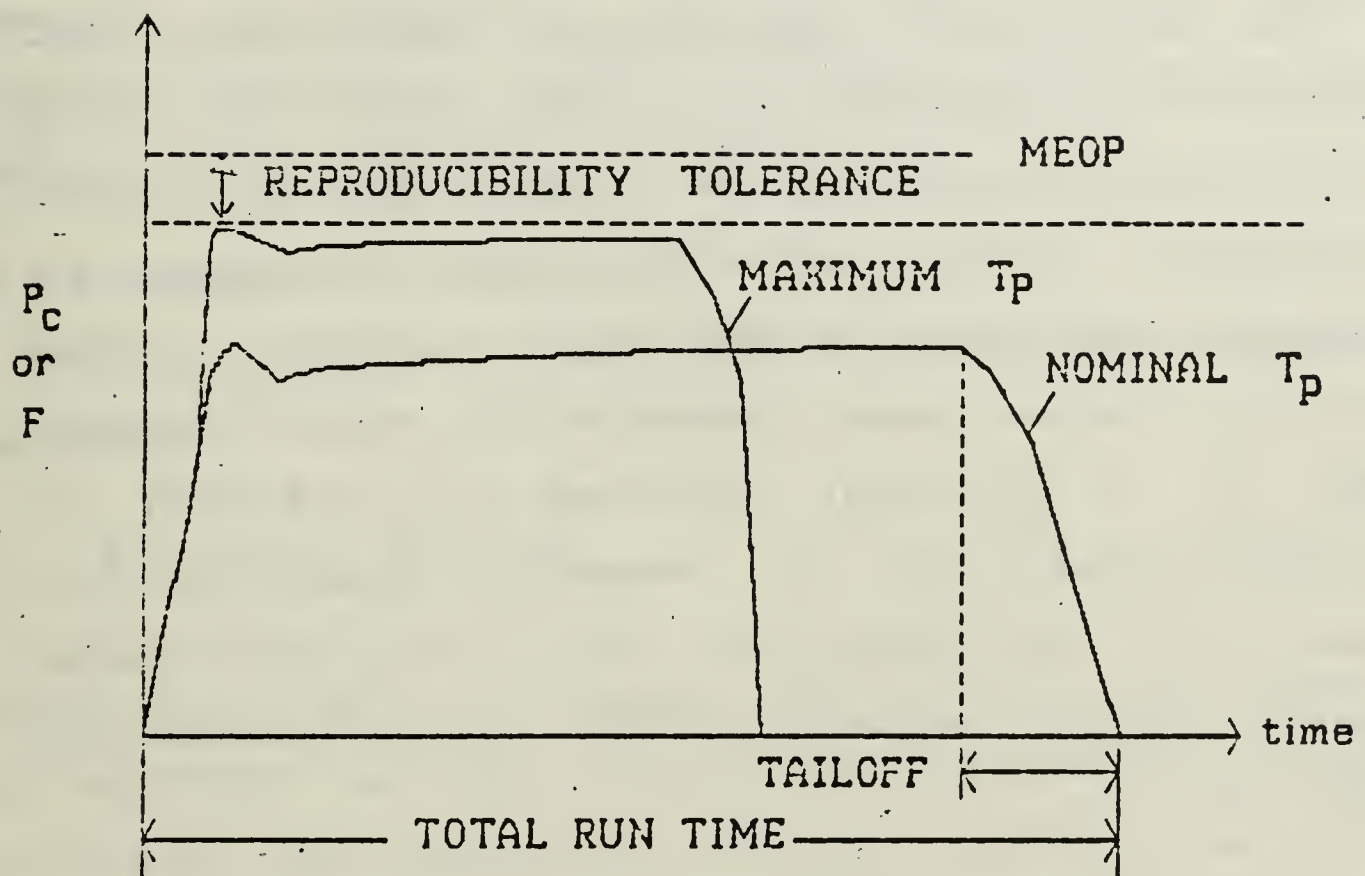


FIGURE 2.

TYPICAL PRESSURE OR THRUST VERSUS TIME PROFILES

d. Allowed Hazard Rating and Allowed Exhaust Signature

The hazard rating requirements have to do with whether the propellant is detonable or non-detonable. Modern high energy propellants are often detonable. The allowed exhaust signature affects the propellant selection through requirements on exhaust smoke and radiation.

C. PROPELLANT SELECTION

From the ballistics performance and mission/vehicle constraints, it is possible to make a preliminary selection of the propellant type that is most likely to give the required performance, internal ballistics, flame temperature and mechanical properties, as well as the necessary storage stability, the best hazard properties and exhaust signature (Ref. 2). A particular propellant will have known (or estimated) burning rate ( $\dot{r}$ ), temperature sensitivity ( $\pi_K$ ), density ( $\rho_p$ ), and composition. Then the nominal chamber pressure ( $P_{C_{nom}}$ ) can be calculated by using the equation (Ref. 3):

$$P_{C_{nom}} = P_{maxtp} \exp (\pi_K (T_{nom} - T_{max})) \quad (2.6)$$

D. THEORETICAL PERFORMANCE COMPUTATION

Following the propellant selection, theoretical performance computations can be made for the specified chamber and ambient pressures. A program such as PEPCODE (Ref. 4),

or the PC version "MICROPEP", will provide data such as thrust coefficient, characteristic exhaust velocity, shifting and frozen equilibrium performance results, optimum nozzle expansion ratio, mole fraction of condensed species in the exhaust, etc.

#### E. NOZZLE GEOMETRY AND MATERIAL SELECTION

The information on theoretical combustion temperature, pressure, gas composition, and burn time, together with geometry constraints, permits the nozzle configuration and material to be selected.

#### F. PERFORMANCE LOSS ESTIMATION

It was assumed that the delivered specific impulse could be written:

$$I_{sp} = I_{sp_{th}} \eta_{C_f} \eta_{C^*} \quad (2.7)$$

where  $I_{sp_{th}}$  is the theoretical specific impulse calculated by "MICROPEP"; and  $\eta_{C_f}$  and  $\eta_{C^*}$  are the thrust coefficient efficiency and characteristic velocity efficiency (or combustion efficiency), respectively.

$\eta_{C_f}$  was computed by summing the effects from the following losses

1. Divergence losses ( $\epsilon_{DIV}$ ),
2. Two-phase flow losses ( $\epsilon_{TP}$ ),
3. Boundary layer loss ( $\epsilon_{BL}$ ),



4. Kinetics loss ( $\epsilon_{KIN}$ ),
5. Submergence loss ( $\epsilon_{SUB}$ ),
6. Erosion loss ( $\epsilon_{EROS}$ ) .

$$\text{Thus, } \eta_{C_f} = 1 - (\epsilon_{DIV} + \epsilon_{TP} + \epsilon_{BL} + \epsilon_{KIN} + \epsilon_{SUB} + \epsilon_{EROS}) / 100 \quad (2.8)$$

The combustion efficiency depends primarily on the residence time ( $t_r$ ), and the latter can be expressed as

$$t_r = (\text{Vol} / \dot{m}) (P_C \bar{M} / 12 \bar{R} T_C) \quad (2.9)$$

where

- Vol is the instantaneous volume of the combustor ( $\text{in}^3$ ),
- $P_C$  is the chamber pressure ( $\text{lbf/in}^2$ ),
- $T_C$  is the chamber temperature ( $^{\circ}\text{R}$ ),
- $\bar{M}$  is the molecular weight,
- $\bar{R}$  is the universal gas constant ( $\text{ft lbf/lb}_{\text{mole}}^{\circ}\text{R}$ ), and
- $\dot{m}$  is the mass discharge rate ( $\text{lbm/sec}$ ).

For example, Figure 3 (Ref. 2) is a plot of specific impulse versus average residence time for aluminized propellants. It shows that the residence time must be somewhere between 10 to 15 msec to obtain a combustion efficiency between 90% and 95%. Increasing the free volume of the combustion chamber will improve the residence time. In this work the initial volume was used in the residence time calculation, i.e., the worst case.

#### G. THROAT AREA AND EXIT AREA

Accurately sizing the throat and exit areas is one of the major goals of the solid propellant rocket motor design.

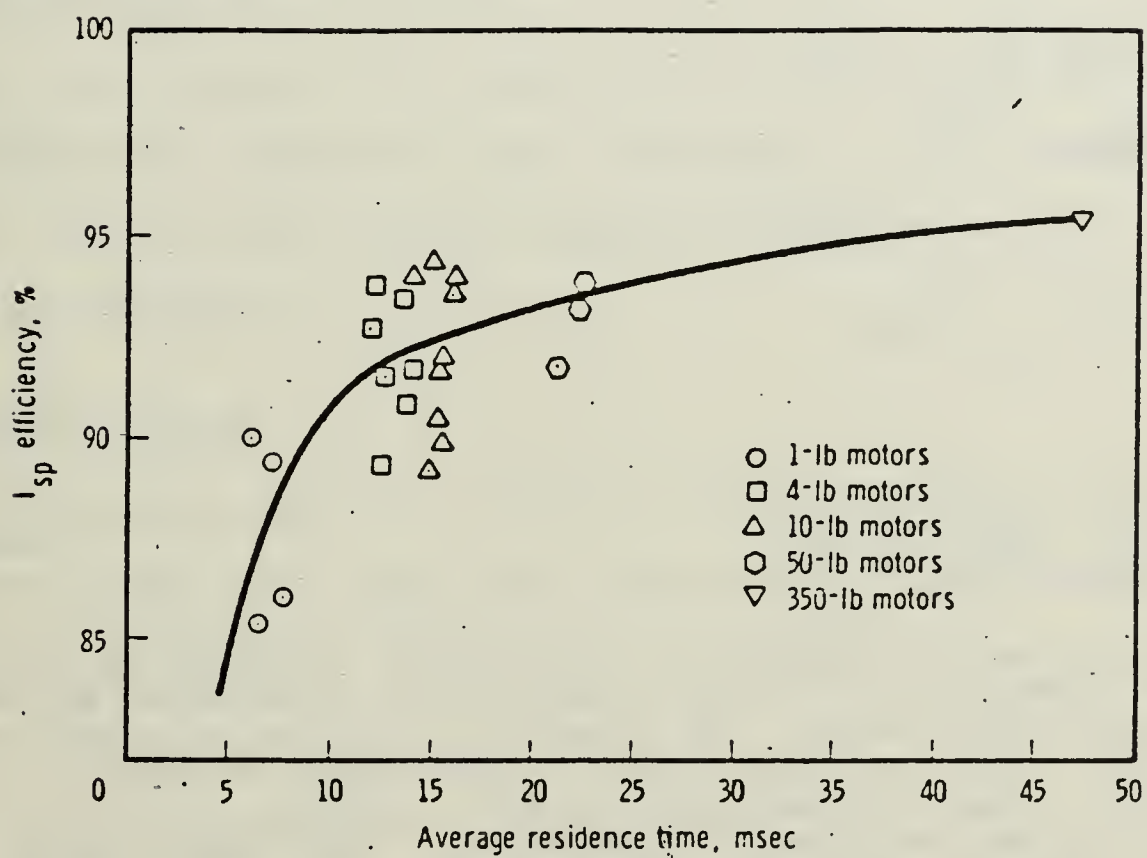


FIGURE 3.

EFFECT OF RESIDENCE TIME ON  $I_{sp}$  EFFICIENCY (Ref 2)



These areas are dependent on several other variables, such as thrust coefficient efficiency, combustion efficiency, specific impulse, and etc.. In the sizing process, it is convenient to start by using the theoretical values. The effects of losses can then be handled iteratively until the solution converges to the final areas. The rest of this section will present the basic algorithm for the throat and exit area sizing process.

The basic definition of specific impulse can be expressed as (Ref. 3):

$$I_{sp_{th}} = \bar{F} / \dot{m} \quad (2.10)$$

where

$$\bar{F} = C_{f_{th}} P_c A_{th} \quad (2.11)$$

Then

$$A_{th} = \frac{\bar{F}}{C_{f_{th}} \eta_{C_f} P_c} \quad (2.12)$$

The theoretical throat area can be estimated by using  $C_{f_{th}}$  for shifting equilibrium flow (from "MICROPEP" - the theoretical performance computation). The losses which are calculated to obtain  $\eta_{C_f}$  depend upon the output from "MICROPEP" and the throat area. Thus, iteration is required to obtain both the losses and throat area.

In summary, the calculation can be conducted in the following steps:

1. Calculate  $A_{th}$  using equation (2.11).
2. Calculate  $\eta_{C_f}$  as discussed above.
3. Calculate  $A_{th}$  using equation (2.12).
4. Repeat steps 2. and 3. until the values for throat area and  $\eta_{C_f}$  converge.

In the current program the iteration was terminated when there was less than a 1% change in  $A_{th}$  per iteration.

The exit area can then be calculated from

$$A_e = A_{th} \epsilon \quad (2.13)$$

where  $\epsilon$  is the exit to throat area ratio.  $\epsilon$  is calculated in "MICROPEP", assuming that the nozzle exit pressure is equal to the local ambient pressure (one-dimensional, ideal flow is assumed).

#### H. GRAIN DESIGN

The primary purpose of grain design is to shape the propellant grain such that the rocket motor can deliver the required performance (thrust-time or pressure-time profile).

In order to be able to select the general configuration of the grain geometry, several parameters must first be determined: the web fraction ( $W_f$ ), volumetric loading fraction ( $V_\ell$ ), and the length-to-diameter ratio ( $L/D$ ) (Ref. 5).  $L/D$  is known from the input data. Web fraction is the fraction of the motor radius that is filled with propellant. Thus,

$$W_f = \frac{\dot{r}_{tb}}{(D/2)} \quad (2.14)$$

The propellant burning rate ( $\dot{r}$ ) is generally expressed in the form:

$$r = a p_c^n \quad (2.15)$$

where  $a$  and  $n$  are empirical constants. They are assumed to be known for the selected propellant. The volumetric loading fraction is defined as the ratio of the volume occupied by the propellant ( $V_p$ ) to the total volume available in the motor for propellant ( $V_a$ ). Thus,

$$V_\ell = \frac{V_p}{V_a} \quad (2.16)$$

where

$$V_a = \left( \frac{\pi D^2}{4} \right) L \quad (2.17)$$

The required propellant volume is found as shown below

$$I_t = \bar{F} t_b = I_{sp} \dot{m} t_b = I_{sp} \frac{W_p}{t_b} t_b = I_{sp} W_p \quad (2.18)$$

$$\text{Thus, } W_p = I_t / I_{sp} \quad (2.19)$$

This yields the required propellant weight ( $W_p$ ) and

$$V_p = \frac{W_p}{\rho_p} \quad (2.20)$$

where  $\rho_p$  is the density or specific weight of the selected propellant. With  $W_f$ ,  $V_\ell$ , and  $L/D$  known, an initial selection of grain geometry can be made (for example, see Ref. 5). For a selected grain configuration, the web versus burning surface area (which is the data needed for

thrust and pressure versus time calculations) can be computed.

## I. THRUST AND PRESSURE VERSUS TIME CALCULATIONS

The thrust and pressure versus time calculations are made using conservation of mass for the combustor(Ref. 3). The mass addition from the burning propellant ( $\dot{m}_g$ ) is equal to the sum of the mass accumulated in the combustor and the mass exhausted from the nozzle ( $\dot{m}_n$ ) as shown in Figure 4. Thus,

$$\dot{m}_g = dM/dt + \dot{m}_n \quad (2.21)$$

$\dot{m}_g$  is the mass of gas generated from the burning propellant.

$$\dot{m}_g = \sum_i \rho_p A_b \dot{r} = \sum_i \rho_p A_b a P_c^n \quad (2.22)$$

The summation is over all propellant grains that are burning at the same time.

$\frac{dM}{dt}$  is the mass accumulating in the combustor.

$$\frac{dM}{dt} = \frac{d}{dt}(\rho_g \text{Vol}) = \rho_g \frac{d\text{Vol}}{dt} + \text{Vol} \frac{d\rho_g}{dt}$$

where (2.23)

$$\frac{d\text{Vol}}{dt} = \sum_i \dot{r} A_b \quad \text{and} \quad \frac{d\rho_g}{dt} \cong \frac{1}{RT_c} \frac{dP_c}{dt}$$

then

$$\frac{dM}{dt} = \frac{P_c}{\bar{R}T_c} \frac{d\text{Vol}}{dt} + \frac{\text{vol}}{\bar{R}T_c} \frac{dP_c}{dt} \quad (2.24)$$

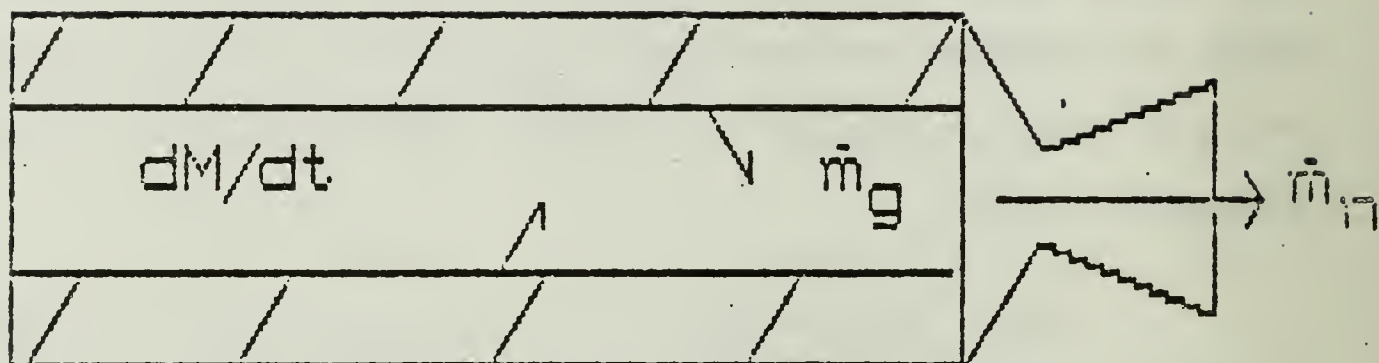


FIGURE 4.

MASS CONSERVATION IN A SOLID PROPELLANT MOTOR

$\dot{m}_n$  is the mass exhausted from the nozzle. For choked flow,

$$\dot{m}_n = \frac{P_c A_{th} g_c}{C^*} \quad (2.25)$$

Combining equations 2.21 through 2.25 results in

$$\sum_i \rho_p A_b a P_c^n = \left( \frac{P_c}{\bar{R} T_c} \right) \frac{dVol}{dt} + \left( \frac{Vol}{\bar{R} T_c} \right) \frac{dP_c}{dt} + \left[ \frac{P_c A_{th} g_c}{C^*} \right] \quad (2.26)$$

Solving for  $dP_c/dt$

$$\frac{dP_c}{dt} = \left( \frac{1}{Vol} \right) \left[ \bar{R} T_c \left( \sum_i \rho_p A_b a P_c^n - \frac{P_c A_{th} g_c}{C^*} \right) - P_c \left( \frac{dVol}{dt} \right) \right] \quad (2.27)$$

Equation 2.27 can be numerically integrated to give  $P_c(t)$ .

The thrust-time behavior can then be obtained from

$$F(t) = n_{c_f} C_f(t) P_c(t) A_{th}(t) \quad (2.28)$$

## J. TERMINAL VELOCITY AND RANGE CALCULATIONS

The last step of solid propellant rocket motor design is to incorporate the designed motor into the desired airframe and make a flight simulation. The purpose of this flight simulation is to verify that the motor can produce the desired range and terminal velocity.



### III. MICROPEP

"MICROPEP" is a microcomputer version of the propellant Evaluation Program (PEP), published in Naval Weapons Center Report NWC-TP-6037, "Theoretical Computations of Equilibrium Compositions, Thermodynamic Properties, and Performance Characteristics of Propellant Systems," by D. R. Cruise, April 1979 (Ref. 4). The code (MICROPEP) can handle 12 different input ingredients and 200 combustion species. It performs the calculations for the thermodynamic properties and performance of propellant systems.

#### A. BASIC ASSUMPTIONS

The basic assumptions of "MICROPEP" are as follows:

1. Equilibrium adiabatic combustion at the nozzle entrance.
2. One-dimensional, isentropic expansion in the nozzle in which the flow can be either a shifting equilibrium flow (assuming chemical equilibrium is maintained throughout the expansion process) or frozen composition flow (assuming the chemical composition of the the flow remains the same throughout the expansion process).
3. Gases were considered to be perfect.
4. Nozzle exit pressure is assumed to be equal to the ambient pressure.



## B. INPUTS

Inputs required by "MICROPEP" are:

1. Composition and mass of each ingredient. Normally the weights of ingredients are chosen to add up to 100 g.

NOTE: Ingredients may be input by the user or they may be selected from an existing data file. In the latter case ingredient serial numbers are used.

For assistance, use README, which should be on the PEPCODED.DAF Data File.

2. Combustion pressure.
3. Nozzle exit pressure. This defines the limits for the expansion process.

## C. OUTPUTS

The program calculates:

1. Combustion product composition, properties, and temperature at the nozzle entrance.
2. Nozzle exit product composition, properties, and temperature for two cases:
  - a. Shifting equilibrium flow
  - b. Frozen composition flow.
3. Required throat area and exit area with no losses, for the same two cases.
4. Theoretical specific impulse, thrust coefficient, and characteristic exhaust velocity for both shifting equilibrium and frozen composition flow.

#### IV. LOSS MECHANISMS

For estimation of the performance losses, a set of empirical formulas suggested by the Propulsion and Energetics Panel of AGARD in AGARD-AR-230 (Ref. 6) were used. Similar methods can also be found in NASA Report SP-8039 (Ref. 7) "Solid Rocket Motor Performance Analysis and Prediction." It is assumed, as in equation 2.7, that the combustion efficiency ( $\eta_{C*}$ ) and thrust coefficient efficiency ( $\eta_{C_f}$ ) can be treated independently. The empirical formulas are valid only for aluminized propellants.

##### A. THRUST COEFFICIENT EFFICIENCY

The thrust coefficient efficiency ( $\eta_{C_f}$ ) can be expressed as in equation 2.8

$$\eta_{C_f} = 1 - (\epsilon_{DIV} + \epsilon_{TP} + \epsilon_{BL} + \epsilon_{KIN} + \epsilon_{SUB} + \epsilon_{EROS}) / 100.0$$

Empirical equations for each of the losses ( $\epsilon$ 's) will be presented and briefly discussed below. More details can be found in Reference 6.

##### 1. Divergence Loss ( $\epsilon_{DIV}$ )

This is the loss due to the radial velocity component of the gas at the nozzle exit plane

$$\epsilon_{DIV} = 50 \left[ 1 - \cos \left( \frac{\alpha + \theta_{ex}}{2} \right) \right] \quad (4.1)$$

$\alpha$  is the nozzle half angle and  $\theta_{ex}$  is the exit angle for a contoured nozzle. For a contoured nozzle,  $\alpha$  is measured to a line drawn from the exit and tangent to the wall at the throat.

## 2. Kinetics Loss ( $\epsilon_{KIN}$ )

This is the loss (or reduction in performance from the value of shifting equilibrium flow) associated with not attaining chemical equilibrium throughout the nozzle expansion process. It is estimated to be 1/3 of the fractional difference between the specific impulse for shifting equilibrium ( $I_{sp_s}$ ) and frozen composition ( $I_{sp_f}$ ). Thus,

$$\epsilon_{KIN} = 33.3 \left[ 1 - \frac{I_{sp_f}}{I_{sp_s}} \right] \quad (4.2)$$

Both  $I_{sp_s}$  and  $I_{sp_f}$  are obtained from 'MICROPEP.'

## 3. Boundary Layer Loss ( $\epsilon_{BL}$ )

The boundary layer loss ( $\epsilon_{BL}$ ) is expressed as

$$\epsilon_{BL} = C_1 \frac{P_C^{0.8}}{D_{th}^{0.2}} [1 + 2 \exp(-C_2 \frac{P_C^{0.8}}{D_{th}^{0.2}} t_b)] [1 + 0.016(\epsilon - 9)] \quad (4.3)$$

This loss accounts for both reduced flow areas and transient heat loss. In equation 4.3,  $P_C$  is in psi,  $D_{th}$  is in inches. The  $C_1$  and  $C_2$  coefficients are

for ordinary nozzles	$C_1 = 0.00365$
	$C_2 = 0.000937$
for steel nozzles	$C_1 = 0.00506$
	$C_2 = 0.0$

#### 4. Two-Phase Flow Loss ( $\epsilon_{TP}$ )

This loss is due primarily to the velocity lag of the condensed species of the combustion products as the mixture passes through the exhaust nozzle,

$$\epsilon_{TP} = C_3 \frac{M_f^{C_4} D_p^{C_5}}{P_c^{0.15} \epsilon^{0.08} D_{th}^{C_6}} \quad (4.4)$$

where

- $D_{th}$  is the diameter of throat in inches
- $D_p$  is the mean  $Al_2O_3$  particle diameter in microns and is calculated from

$$D_p = 3.39 D_{th}^{0.4692}$$

- $P_c$  is chamber pressure in psia
- $C$ 's are dependent on the diameter of the throat

$$C_4 = 0.5$$

$D_{th} < 1:$	$C_3 = 9$	$C_5 = 1$	$C_6 = 1$
$1 \leq D_{th} \leq 2:$	$C_3 = 9$	$C_5 = 1$	$C_6 = 0.08$
$D_{th} > 2$ and $D_p < 4:$	$C_3 = 13.4$	$C_5 = 0.8$	$C_6 = 0.8$
$D_{th} > 2$ and			
$4 \leq D_p \leq 8:$	$C_3 = 10.2$	$C_5 = 0.8$	$C_6 = 0.4$
$D_{th} > 2$ and $D_p > 8:$	$C_3 = 7.58$	$C_5 = 0.8$	$C_6 = 0.33$

- $M_f$  is the mole fraction of condensed phase in moles/100 gm of reactants.

## 5. Submergence Loss ( $\epsilon_{\text{SUB}}$ )

This loss is expressed as

$$\epsilon_{\text{SUB}} = 0.0684 \left( \frac{P_c \epsilon}{A_{\text{th}}} \right)^{0.8} \frac{S^{0.4}}{D_{\text{th}}^{0.2}} \quad (4.5)$$

It is due to the nozzle configuration for a submerged nozzle where S is the submergence length in inches (the length that the nozzle is imbedded in the combustion chamber).

## 6. Nozzle Erosion Loss ( $\epsilon_{\text{EROS}}$ )

This loss results from nozzle erosion during the burn and is expressed as

$$\epsilon_{\text{EROS}} = \left[ 1 - \frac{I_{\text{sp}_m}}{I_{\text{sp}_{\text{th}}}} \right] \times 100 \quad (4.6)$$

$I_{\text{sp}_{\text{th}}}$  is the theoretical  $I_{\text{sp}}$  for the initial nozzle expansion ratio and  $I_{\text{sp}_m}$  is the theoretical  $I_{\text{sp}}$  for the mean expansion ratio.  $I_{\text{sp}_m}$  is determined by interpolation of  $I_{\text{sp}_{\text{th}}}$  versus the nozzle expansion ratio data from "MICROPEP."

## B. COMBUSTION EFFICIENCY

NASA Report SP-8064 (Ref. 2) states that the combustion efficiency ( $\eta_{\text{C}}^*$ ) is determined by "the completeness of metal combustion within the motor and by the degree to which combustion products reach chemical equilibrium among themselves." These effects depend primarily on the residence time ( $t_r$ ) as expressed in equation 2.9. An  $\eta_{\text{C}}^*$  of



90-95% can be attained if residence time is 10-15 msec (see Figure 3).

### C. PROGRAM

The subroutines which solve for the thrust and combustion efficiencies are listed in Appendix A, Subroutine PFE and Subroutine LOSCF. Basically, they followed the method discussed in Chapter II. The algorithm is shown below

1. Initialize  $C_f$  (coefficient of thrust) as  $C_{f_{th}}$   
(theoretical coefficient of thrust from "MICROPEP"  
for shifting equilibrium).
2. Calculate  $A_{th}$  and  $D_{th}$ :

$$D_{th} = 2 \left( \frac{\bar{F}}{C_{f_{th}} P_c \pi} \right)^{1/2}$$

3. Calculate  $\eta_{C_f}$  using the relation

$$\eta_{C_f} = 1 - (\epsilon_{DIV} + \epsilon_{BL} + \epsilon_{TP} + \epsilon_{KIN} + \epsilon_{SUB} + \epsilon_{EROS}) / 100$$

4. Calculate  $C_f$  using

$$C_f = C_{f_{th}} \eta_{C_f}$$

5. Correct  $D_{th}$  using

$$D_{th} = 2 \left( \frac{\bar{F}}{C_f \cdot P_c \pi} \right)^{1/2}$$

6. Repeat Steps 3 to 5 until  $A_{th}$  converges.

The reason that  $A_{th}$  was used for the iteration variable was that  $\eta_c$  (through  $\epsilon_{BL}$ ,  $\epsilon_{TP}$ , and  $\epsilon_{SUB}$ ) depends upon  $A_{th}$ .



## V. GRAINS

"GRAINS" is PC based code for the design of radial sided star grains. The original version was written by G. J. Woten and R. McCormick of CSD, United Technologies, November 1984. It was then modified by LT G. Liston of AFWAL/Port, December 1984. The general shape of this grain and the geometric variables are shown in Figure 5.

"GRAINS" can be used in either of two modes: the "Design Mode" or the "Burnback Model."

### A. "DESIGN MODE"

In the "Design mode" the program solves for geometries that satisfy input requirements on the number of star points required port area, perimeter factor, web, and etc., together with the allowed tolerances on these parameters.

The geometric constraints for the grain are determined from the propellant characteristic and motor constraints. For example:

$$A_{port} = \left(\frac{\pi}{4}\right) D^2 \left[ \left( 1 - \left( \frac{\bar{F} t_b}{I_{sp} \rho_p} \right) \right) \right]$$

$D$ ,  $t_b$  and  $\bar{F}$  are motor inputs requirements and  $I_{sp}$  and  $\rho_p$  are determined once the propellant has been selected.

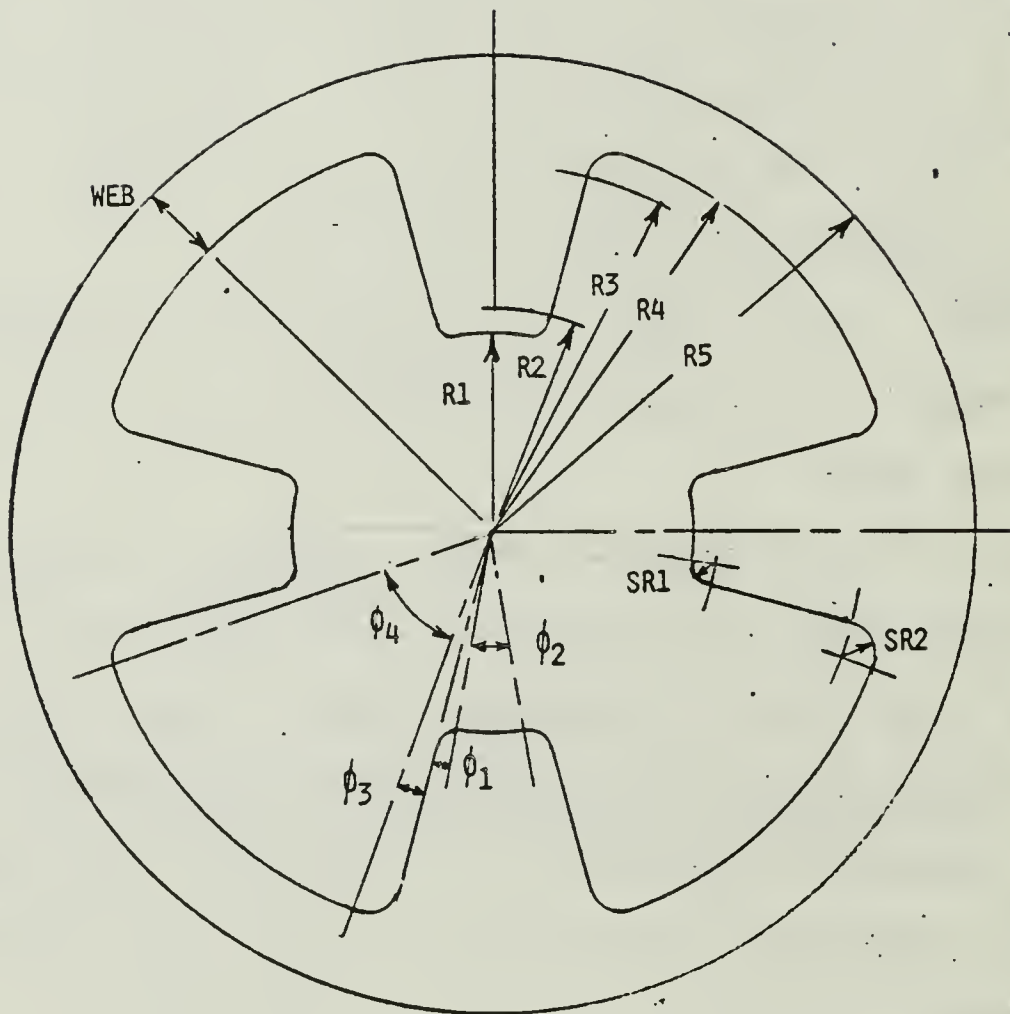


FIGURE 5.

NOMENCLATURE FOR "GRAINS" DESIGN MODE

## B. "BURNBACK MODE"

The "burnback mode" uses the length of the grain, initial port area, perimeter, and the results from "Design Mode" to calculate the perimeter, perimeter factor, port area, and burning surface area as functions of the web burned.

## C. COMMENTS ON PROGRAM OPERATION

Care must be used for the inputs and input tolerances, otherwise no acceptable solutions will be obtained. It is best to start with large allowable tolerances on  $A_{port}$ , etc. (typically 20%). After initial solutions are found in "Design" for the number of star points, range of web thicknesses, etc., the range of the input variables can be reduced along with the allowable tolerances.

## VI. ROCKET

"ROCKET" is also a PC-based computer code. It was originally written by The Lockheed Company for a mainframe computer. Later, it was transferred for use on the IBM-PC by J. P. Francis of the Naval Weapons Center (August 1985). The function of "ROCKET" is to calculate the pressure-time and thrust-time profiles for the motor, including theoretical calculations for both ignition and tailoff transients. The description of the motor can include igniters, multiple propellant grains, and motor insulation. In this thesis work the program was restricted to a motor with a single grain configuration.

### A. BASIC ASSUMPTIONS

The assumptions made in "ROCKET" are:

1. The combustion products are ideal gases.
2. Propellant burning rate follows the expression
$$\dot{r} = aP_C^n$$
3. There are no effects of mass addition or erosive burning in the combustion chamber.
4.  $C^*$  varies with  $P_C$  in the form of

$$C^* = C_{ref}^* \left( \frac{P_C}{P_{ref}} \right)^x$$

5. The temperature sensitivity ( $\pi_K$ ) is used to correct for the effects of propellant temperature on the propellant burning rate and chamber pressure.

$$\dot{r}_{T_p} = \dot{r}_{(70^\circ)} e^{0.01\sigma_p(T_p-70^\circ)}$$

where

$$\sigma_p = (1-n)\pi_K$$

## B. ANALYTICAL BACKGROUND

The program is based upon the method discussed in Chapter II, i.e., it numerically integrates equation (2.27) to obtain  $P_c(t)$ . Then it calculates  $C_f$  with a fixed ratio of specific heats ( $\gamma$ ). Thrust is then calculated using equation

$$F = C_f(t)P_c(t)A_{th}(t)\lambda C_D$$

where  $\lambda$  is nozzle divergence loss and  $C_D$  is the nozzle discharge coefficient.  $\lambda$  and  $C_D$  are only two parts of  $\eta_{C_f}$ . In order to use ROCKET in the combined program,  $\lambda$  was set to unity and  $C_D$  was equated to  $\eta_{C_f}$ .

## C. INPUTS

Inputs to "ROCKET" include:

1. General motor parameters:
  - a. Throat area ( $A_{th}$ )
  - b. Nozzle exit area ( $A_e$ )
  - c. Total motor volume ( $V_a$ )
  - d. Ambient temperature and pressure

- e. Nozzle throat plug closure blowout pressure (nozzle is plugged until this pressure is exceeded, typically 35 psia)
  - f. Initial pressure in the motor ( $P_{zero}$ , typically 15 psia)
  - g. Nozzle divergence loss  $\lambda$  (set equal to 1 in this work)
  - h. Ratio of specific heats for chamber gases ( $\gamma$ ) (this was obtained from "MICROPEP" chamber conditions)
  - i. Design pressure ( $P_c$ )
  - j. Throat radial erosion rate (erosr).
2. Motor element descriptions:
- a. Propellant burning rate ( $\dot{r}$ )
  - b. Burning rate exponent ( $n$ )
  - c. Propellant temperature sensitive ( $\pi_K$ )
  - d. Burning rate reference pressure
  - e. Propellant  $C^*$
  - f. Pressure correction exponent for  $C^*$
  - g. Propellant density ( $\rho_p$ )
  - h. A table of web versus burning surface area.

#### D. OUTPUTS

The outputs include:

- 1. A pressure versus time table
- 2. A thrust versus time table



3. The free volume, propellant consumed (weight), and throat area versus time table.

## VII. FLYIT

"FLYIT" is a three-degree-of-freedom (range, altitude and angle of attack) trajectory simulation program originally developed by G. Burgner of the Propulsion Analysis Branch, Naval Weapons Center (NWC). A User's guide was later published by Y.G. Coenen (Ref. 8). The program can simulate vertical-plane trajectories which include take-off, climbs, cruises, landing, and rocket boost. It is a tool to synthesize and analyze the trajectories of air-to-surface, and surface-to-surface missiles.

The basic structure of "FLYIT" consists of five functional sub-groups, they are:

- Atmospheric
- Trajectory controls
- Aerodynamics
- Rocket boosters
- Sustainer propulsion.

Users are allowed to select a different option in each functional group to simulate different flight profiles with different propulsion systems. Through the use of "FLYIT" it is possible to estimate the terminal velocity and range of certain propulsion systems.

"FLYIT" was not incorporated into the main body of the present program due to time limitations.

## VIII. COMBINED PROGRAM

The combined program ("SPRMD") is listed in Appendix and basically follows the design process discussed in Chapter II. The basic structure of this program is shown on Figure 6.

This program combines "MICROPEP" (to calculate the theoretical thermodynamic performance of the propellant), "PFE," and "LOSCF" (to calculate  $\eta_{CF}$ , and to estimate  $\eta_{C^*}$ , and size the throat and exit areas), "GRAINS" (to provide web burned versus burning surface area for radially sided star grains), and "ROCKET" (to compute the pressure-time and thrust-time profiles). Inputs to the program include "INPUT0" (the initial mission requirement inputs), "INPUT1" (inputs for "MICROPEP"), "INPUT2" (inputs for "GRAINS"), and "RCKTIN" (inputs for "ROCKET"). All of these programs comprise an interactive program for solid propellant rocket motor preliminary design.

### A. ALGORITHM

A simplified algorithm of this program can be briefly listed as follows:

#### 1. "INPUT0"

Input the basic ballistic and mission/vehicle requirements. Calculate the required average

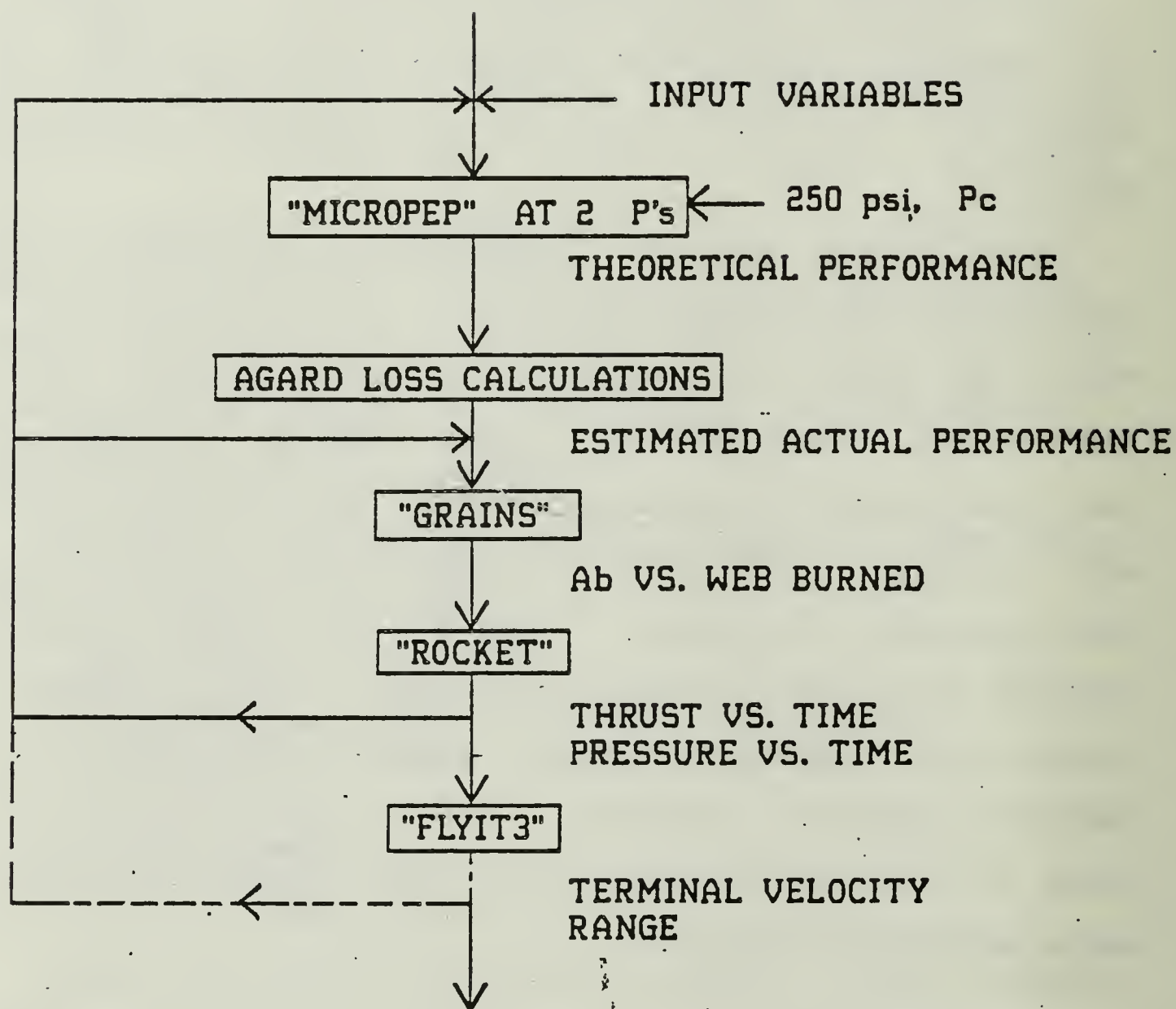


FIGURE 6.

FLOW CHART FOR THE COMBINED PROGRAM

requirements. Calculate the required average chamber pressure for a specific propellant and propellant temperature.

2. "INPUT1"

Input propellant composition, chamber pressure, and ambient pressure. Create a file for 'MICROPEP.'

3. "MICROPEP"

Perform the theoretical performance calculations for the selected propellant.

4. "PFE"

Performs the following functions:

- a. Estimates the combustion efficiency
- b. Calculates the delivered specific impulse
- c. Sizes the throat area, exist area, calculates perimeter factor, perimeter, required web, required burning rate, and etc.

5. "INPUT2"

Input the geometrical description of the star grain and propellant characteristics. Create a file to accommodate the processing of "GRAINS." Other grain design programs (such as SPP) can be readily incorporated.

6. "GRAINS"

Designs the star grain and calculates web versus burning surface area.

7. "RCKTIN"

Uses the results from the previous programs to create a file for "ROCKET."

8. "ROCKET"

Calculates the pressure-time and thrust-time profiles.

B. BRANCHING

The algorithm discussed above also provides for the capability of branching. For example, if the desired  $P_c$  versus time is not attained, the user can either re-do the grain design and/or select other propellant properties.



## IX. EXAMPLE OF DESIGN PROGRAM

The initial requirements which are input into the program are shown in Table 1, together with a selected value for the temperature sensitivity of the propellant ( $\pi_K$ ). A reproducibility tolerance of 7% was chosen.

The nominal operating pressure at  $T_p = 70^\circ\text{F}$  was calculated to be 1030 psia and the required propellant burning rate for a web fraction of 0.5 was 0.615 in/sec.

A composite propellant consisting of 78% AP, 12% HTPB, and 10% Al was selected. "MICROPEP" was then run for pressures of 250 psia and the nominal  $P_c$  value of 1030 psi. Outputs from "MICROPEP" are presented in Table 2.

TABLE 1

INPUT PARAMETERS

---

AVERAGE THRUST, LBF.....	14250.0
BURN TIME, SEC.....	6.50
MINIMUM THRUST REQUIRED, LBF.....	8000.000000
MOTOR LENGTH, INCH.....	40.00
MOTOR DIAMETER, INCH.....	16.00
MAXIMUM EXPECTED OPERATING PRESSURE...	1300.0
TPMAX, F.....	150.0
TPNOM, F.....	70.0
TPMIN, F.....	-65.0
TEMPERATURE SENSITIVITY, %/F.....	0.200
NOMINAL CHAMBER PRESSURE, PSI.....	1030.2
REQUIRED BURNING RATE, IN/SEC.....	0.615
ALTITUDE, FT.....	10000.
AMBIENT PRESSURE, PSI.....	10.13
AMBIENT TEMPERATURE, R.....	483.1

TABLE 2

MICROPEP OUTPUT FOR  $P_c = 250$  AND 1030 PSIA:  
 $P_c = 10.0$  PSIA. 78% AP, 12% HTPB, 10% Al

DESIGN 1 Case 1 of 2

## DH DENS COMPOSITION

AMMONIUM PERCHLORATE (AP)	-602	0.07040	1CL	4H	1N	4O
HTPB (SINCLAIR)	13	0.03320	103H	73C	1O	
ALUMINUM (PURE CRYSTALLINE)	0	0.09760	1AL			

INGREDIENT WEIGHTS (IN ORDER) AND TOTAL WEIGHT (LAST ITEM IN LIST)

78.0000 12.0000 10.0000 100.0000

## INGREDIENT VOLUME RATIOS

AMMONIUM PERCHLORATE (AP)	70.487%	HTPB (SINCLAIR)	22.995%
ALUMINUM (PURE CRYSTALLINE)	6.518%		

THE PROPELLANT DENSITY IS 0.06362 LB/CU-IN OR 1.7610 GM/CC

## NUMBER OF GRAM ATOMS OF EACH ELEMENT PRESENT IN INGREDIENTS

3.895570 H	0.878965 C	0.663847 N	2.667428 O
0.370645 AL	0.663847 CL		
CP =	43.62668610		

## CHAMBER RESULTS FOLLOW:

T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V	MOL WT
3248.	5388.	17.01	250.00	-46.80	240.56	1.1990	3.644	4.667	27.44

DAMPED AND UNDAMPED SPEED OF SOUND= 3211.743 AND 3563.987 FT/SEC

HEAT CONTENT (298 REF) 1253.397 CAL/GR 2257.631 BTU/LBM

0.98321 H2O	0.71991 CO	0.58380 H2	0.57339 HCl
0.32835 N2	0.17947 Al2O3*	0.15900 CO2	0.11256 H
0.07546 HO	0.07476 Cl	0.00880 O	0.00709 NO
5.93E-03 O2	4.51E-03 AlOCl	3.65E-03 AlCl2	3.20E-03 AlCl
1.32E-04 AlCl3	1.28E-04 Cl2	1.19E-04 AlO	6.37E-05 Al
2.31E-05 CHO	1.73E-05 NH	1.61E-05 N	1.21E-05 HO2
7.13E-06 NH3	5.55E-06 NHO	5.24E-06 Al2O	4.85E-06 AlH
2.03E-06 CNH	1.91E-06 AlHO2	1.09E-06 CH2O	
CP =	41.92294693		

## EXHAUST RESULTS FOLLOW:

T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V	MOL WT
2313.	3704.	0.69	10.13	-108.91	240.56	1.1995	3.510	0.196	28.49

DAMPED AND UNDAMPED SPEED OF SOUND= 2650.051 AND 2952.060 FT/SEC

HEAT CONTENT (298 REF) 851.166 CAL/GR 1533.130 BTU/LBM

1.01958 H2O	0.67108 CO	0.64916 HCl	0.59218 H2
0.33181 N2	0.20785 CO2	0.18284 Al2O3&	0.01785 H
0.01421 Cl	0.00497 HO	0.00233 Al2O3*	0.00021 NO
1.33E-04 AlCl2	1.04E-04 O	1.01E-04 AlOCl	7.51E-05 O2
4.03E-05 AlCl	1.25E-05 AlCl3	9.06E-06 Cl2	

TABLE 2 CONTINUED)

MICROPEP OUTPUT FOR  $P_c = 250$  AND 1030 PSIA:  
 $P_c = 10.0$  PSIA. 78% AP, 12% HTPB, 10% Al

---

PERFORMANCE: FROZEN ON FIRST LINE, SHIFTING ON

SECOND LINE

ISP	GAMMA	T*	P*	C*	CF	OPT EX	D-ISP	A*M.	EX T
226.7	1.1835	2975.	9.65	5060.1	1.442	4.31	399.2	0.62924	1976.
232.5	1.1497	3045.	9.77	5082.8	1.472	4.72	409.4	0.63205	2313.

BOOST VELOCITIES FOR PROPELLANT DENSITY OF 0.06362 (S.G. OF 1.761)

5./23451.	10./18585.	15./15857.	25./12612.	30./11520.	55./ 8215.
60./ 7788.	69./ 7128.	71./ 6998.	88./ 6064.	100./ 5548.	150./ 4113.
175./3647.	200./3277.	300./2336.	1000./ 780.	3000./ 269.	5000./ 163.

EXP. RATIO	EXIT PRESS ATM	EXIT PRESS SI	EXIT TEMP K	OPTIMUM IMPULSE SEC	OPTIMUM IMPULSE SI	VACUUM IMPULS SEC	VACUUM IMPULS SI	SEA LV IMPULS SEC	SEA LV IMPULS SI
1.	9.769	989.6	3044.	104.9	1029.	195.7	1919.	186.4	1846.
2.	3.256	329.9	2678.	175.0	1716.	235.5	2309.	216.9	2149.
3.	1.215	123.0	2386.	214.4	2103.	248.3	2435.	220.4	2184.
4.	0.833	84.4	2314.	226.6	2223.	257.6	2526.	220.5	2184.
5.	0.644	65.3	2313.	234.5	2300.	264.5	2593.	218.0	2160.
6.	0.523	53.0	2311.	240.7	2361.	269.9	2647.	214.1	2121.
7.	0.439	44.5	2310.	245.8	2410.	274.4	2690.	209.3	2074.
8.	0.378	38.3	2310.	250.1	2453.	278.2	2728.	203.9	2019.
9.	0.331	33.5	2309.	253.8	2489.	281.5	2760.	197.9	1960.
10.	0.294	29.8	2308.	257.1	2521.	284.4	2789.	191.5	1897.
11.	0.264	26.8	2307.	260.0	2550.	287.0	2814.	184.8	1831.
12.	0.240	24.3	2307.	262.6	2575.	289.3	2837.	177.9	1762.
13.	0.219	22.2	2306.	265.0	2599.	291.5	2858.	170.7	1691.
14.	0.202	20.5	2306.	267.2	2620.	293.5	2878.	163.4	1619.
15.	0.187	19.0	2305.	269.2	2640.	295.3	2896.	155.9	1545.
16.	0.174	17.7	2305.	271.1	2658.	297.0	2912.	148.3	1469.
17.	0.163	16.5	2305.	272.8	2675.	298.5	2928.	140.6	1393.
18.	0.153	15.5	2304.	274.4	2691.	300.0	2942.	132.8	1316.
19.	0.144	14.6	2304.	276.0	2706.	301.4	2956.	124.9	1237.
20.	0.136	13.8	2304.	277.4	2720.	302.7	2969.	116.9	1158.
21.	0.129	13.1	2303.	278.8	2734.	304.0	2981.	108.9	1079.
22.	0.123	12.4	2303.	280.1	2746.	305.1	2992.	100.8	998.
23.	0.117	11.8	2303.	281.3	2758.	306.3	3003.	92.6	917.
24.	0.112	11.3	2302.	282.5	2770.	307.3	3014.	84.4	836.
25.	0.107	10.8	2302.	283.6	2781.	308.3	3024.	76.1	754.



# TABLE 2 (CONTINUED)

MICROPEP OUTPUT FOR  $P_c = 250$  AND 1030 PSIA:  
 $P_c = 10.0$  PSIA. 78% AP, 12% HTPB, 10% Al

DESIGN 1 Case 2 of 2

## DH DENS COMPOSITION

AMMONIUM PERCHLORATE (AP)	-602	0.07040	1CL	4H	1N	40
HTPB (SINCLAIR)	13	0.03320	103H	73C	10	
ALUMINUM (PURE CRYSTALLINE)	0	0.09760	1AL			

INGREDIENT WEIGHTS (IN ORDER) AND TOTAL WEIGHT (LAST ITEM IN LIST)

78.0000 12.0000 10.0000 100.0000

## INGREDIENT VOLUME RATIOS

AMMONIUM PERCHLORATE (AP)	70.487%	HTPB (SINCLAIR)	22.995%
ALUMINUM (PURE CRYSTALLINE)	6.518%		

THE PROPELLANT DENSITY IS 0.06362 LB/CU-IN OR 1.7610 GM/CC

## NUMBER OF GRAM ATOMS OF EACH ELEMENT PRESENT IN INGREDIENTS

3.895570 H	0.878965 C	0.663847 N	2.667428 O
0.370645 AL	0.663847 CL		
CP =	43.75085831		

## CHAMBER RESULTS FOLLOW:

T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V	MOL WT
3375.	5616.	70.08	1030.24	-46.80	230.37	1.1952	3.597	19.485	27.80

DAMPED AND UNDAMPED SPEED OF SOUND= 3247.693 AND 3603.495 FT/SEC

HEAT CONTENT (298 REF) 1309.442 CAL/GR 2358.580 BTU/LBM

1.01084 H2O	0.71716 CO	0.59375 HCl	0.57367 H2
0.32895 N2	0.17941 Al2O3*	0.16171 CO2	0.07526 H
0.05727 HO	0.05233 Cl	0.00586 NO	0.00506 AlCl2
4.49E-03 O	3.70E-03 AlOCl	3.15E-03 O2	2.63E-03 AlCl
3.14E-04 AlCl3	1.83E-04 Cl2	7.24E-05 AlO	5.77E-05 CHO
3.63E-05 Al	2.75E-05 NH	2.71E-05 NH3	1.55E-05 N
1.33E-05 HO2	9.39E-06 NHO	8.06E-06 CNH	5.08E-06 AlH
4.45E-06 CH2O	3.50E-06 Al2O	2.16E-06 AlHO2	
CP =	40.18283081		

## EXHAUST RESULTS FOLLOW:

T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V	MOL WT
1852.	2874.	0.69	10.13	-130.14	230.37	1.2087	3.491	0.197	28.64

DAMPED AND UNDAMPED SPEED OF SOUND= 2373.392 AND 2644.581 FT/SEC

HEAT CONTENT (298 REF) 659.260 CAL/GR 1187.465 BTU/LBM

0.98547 H2O	0.66303 HCl	0.63198 CO	0.63022 H2
0.33192 N2	0.24696 CO2	0.18531 Al2O3&	0.00097 H
7.87E-04 Cl	1.10E-04 HO	2.78E-06 AlCl2	2.25E-06 NO
2.21E-06 AlCl3	1.52E-06 NH3		

PERFORMANCE: FROZEN ON FIRST LINE, SHIFTING ON SECOND LINE

TABLE 2 (CONTINUED)

MICROPEP OUTPUT FOR  $P_C = 250$  AND 1030 PSIA:  
 $P_C = 10.0$  PSIA. 78% AP, 12% HTPB, 10% Al

---

ISP	GAMMA	T*	P*	C*	CF	OPT EX	D-ISP	A*M.	EX T
262.5	1.1907	3081.	39.69	5084.9	1.661	12.28	462.2	0.15344	1610.
269.3	1.1617	3139.	40.09	5126.9	1.690	13.25	474.2	0.15471	1852.

BOOST VELOCITIES FOR PROPELLANT DENSITY OF 0.06362 (S.G. OF 1.761)

5./27165.	10./21528.	15./18368.	25./14609.	30./13344.	55./ 9516.
60./ 9021.	69./ 8257.	71./ 8106.	88./ 7024.	100./ 6426.	150./ 4764.
175./4224.	200./3796.	300./2705.	1000./ 904.	3000./ 312.	5000./ 188.

EXP. RATIO	EXIT PRESS ATM	EXIT PRESS SI	EXIT TEMP K	OPTIMUM IMPULSE SEC	OPTIMUM IMPULSE SI	VACUUM IMPULS SEC	VACUUM IMPULS SI	SEA LV IMPULS SEC	SEA LV IMPULS SI
1.	40.059	4057.9	3139.	106.6	1045.	197.7	1939.	195.4	1936.
2.	13.353	1352.6	2722.	176.8	1734.	237.6	2330.	233.0	2308.
3.	4.904	496.8	2391.	216.7	2125.	250.1	2453.	243.3	2410.
4.	3.289	333.2	2270.	229.5	2250.	259.4	2544.	250.3	2479.
5.	2.435	246.7	2183.	238.3	2337.	266.0	2609.	254.7	2523.
6.	1.913	193.8	2115.	245.0	2402.	271.1	2658.	257.4	2550.
7.	1.563	158.3	2060.	250.3	2454.	275.1	2698.	259.2	2568.
8.	1.314	133.1	2014.	254.6	2497.	278.5	2731.	260.3	2579.
9.	1.129	114.3	1975.	258.3	2532.	281.4	2759.	260.9	2584.
10.	0.986	99.9	1940.	261.4	2563.	283.8	2783.	261.1	2586.
11.	0.873	88.4	1910.	264.2	2590.	286.0	2805.	261.0	2585.
12.	0.781	79.1	1882.	266.6	2615.	287.9	2824.	260.7	2582.
13.	0.706	71.5	1858.	268.8	2636.	289.7	2841.	260.1	2577.
14.	0.643	65.1	1835.	270.8	2655.	291.3	2856.	259.4	2570.
15.	0.589	59.7	1814.	272.6	2673.	292.7	2870.	258.6	2562.
16.	0.543	55.0	1795.	274.3	2690.	294.0	2883.	257.6	2552.
17.	0.503	51.0	1778.	275.8	2705.	295.2	2895.	256.6	2542.
18.	0.468	47.4	1761.	277.2	2718.	296.4	2906.	255.5	2531.
19.	0.438	44.3	1746.	278.5	2731.	297.4	2917.	254.2	2519.
20.	0.411	41.6	1731.	279.8	2743.	298.4	2927.	253.0	2506.
21.	0.386	39.1	1717.	280.9	2755.	299.4	2936.	251.6	2493.
22.	0.365	36.9	1704.	282.0	2766.	300.3	2944.	250.2	2479.
23.	0.345	34.9	1692.	283.0	2776.	301.1	2952.	248.8	2465.
24.	0.327	33.1	1681.	284.0	2785.	301.9	2960.	247.3	2450.
25.	0.311	31.5	1670.	284.9	2794.	302.6	2968.	245.8	2435.



The output from "MICROPEP" indicated the following

$$C_{th}^* = 5126.9 \text{ ft/sec}$$

$$I_{sp_{th}} = 269.3 \text{ lbf sec/lbm}$$

$$\epsilon = 13.25$$

$$\text{Moles of condensed Al}_2\text{O}_3/100 \text{ gm} = 0.1794$$

$$\rho_p = .0636 \text{ lbm/in}^3$$

The AGARD-AR-230 empirical equations were then used to estimate the value for  $\eta_C$ .  $\eta_{C^*}$  was chosen to be 0.93. For  $f$  the calculated residence time of 7.2 msec, Figure 3, indicates that a better value may have been approximately 0.87. As discussed above, the losses are iterated with the throat area. The resulting losses and throat area are presented in Table 3.

Once the losses have been estimated  $I_{sp}$  can be determined from

$$I_{sp} = \eta_{C_f} \eta_{C^*} I_{sp_{th}}$$

The following parameters were then calculated:

$$\dot{m} = \bar{F}/I_{sp}$$

$$V_p = I_t/I_{sp} \rho_p$$

$$V_\ell = V_p/V_a$$

$$D_{pe} = (\sqrt{1-V_\ell}) D$$

$$A_p = \left(\frac{\pi}{4}\right) D_{pe}^2 = \frac{\pi}{4} D^2 (1-V_\ell)$$

$$J = A_{th}/A_p$$

These parameters are shown in Table 4.

TABLE 3

## ESTIMATED PERFORMANCE LOSSES

---

PERCENT DIVERGENCE LOSS.....	1.704
PERCENT TWO PHASE FLOW LOSS.....	3.202
PERCENT BOUNDARY LAYER LOSS.....	1.828
PERCENT KINETIC LOSS.....	0.849
PERCENT SUBMERGENCE LOSS.....	0.000
PERCENT EROSION LOSS.....	0.007
THRUST COEFFICIENT EFFICIENCY.....	0.924
Etacf= 0.924 Cfc= 1.562 Ath= 8.856	
PERCENT DIVERGENCE LOSS.....	1.704
PERCENT TWO PHASE FLOW LOSS.....	3.199
PERCENT BOUNDARY LAYER LOSS.....	1.783
PERCENT KINETIC LOSS.....	0.849
PERCENT SUBMERGENCE LOSS.....	0.000
PERCENT EROSION LOSS.....	0.007
THRUST COEFFICIENT EFFICIENCY.....	0.925

TABLE 4

## CALCULATED MOTOR DATA

---

THRUST COEFFICIENT.....	1.563
ETACF.....	0.925
SPECIFIC IMPULSE, LBF SEC/LBM.....	231.587
MASS FLOW RATE, LBM/SEC.....	61.532
PROPELLANT VOLUME, CU IN.....	6286.8
NOZZLE THROAT AREA, SQ IN.....	8.851
NOZZLE EXIT AREA, SQ IN.....	117.290
EQUIVALENT PORT DIAMETER, IN.....	7.476
PORT AREA, SQ IN .....	43.893
PERIMETER FACTOR.....	2.489
REQUIRED WEB, IN.....	2.500
REQUIRED WEB FRACTION.....	0.312
VOLUMETRIC LOADING.....	0.782
LENGTH TO DIAMETER RATIO.....	2.500
RESIDENCE TIME, MSEC.....	7.256
THROAT TO PORT AREA RATIO (J FACTOR)...	0.202
REQUIRED BURNING RATE, IN/SEC.....	0.385

At this point the following expressions remain to be satisfied:

$$\left. \begin{aligned} \text{Perimeter Factor} &= \text{PFAC} = P_{\text{wetted}} / \pi D_{\text{pe}} \\ A_b &= P_{\text{wetted}} L \\ \dot{m} &= \rho_p A_b \dot{r}_{\text{P}_{\text{cnom}}} \\ \dot{r} &= \text{web} / t_b \end{aligned} \right\} \text{PFAC} = A_b / \pi D_{\text{pe}} L$$

In these three expressions the unspecified variables are PFAC,  $A_b$ ,  $\dot{r}$ , and web.

For a selected web or  $\dot{r}$  the other parameters can be determined. For example, in the current problem Table E summarizes the required values for selected web thicknesses.

TABLE 5			
REQUIRED PARAMETERS FOR SELECTED WEBS			
web(in)	$\dot{r}$ (in/sec)	$A_b$ (in <sup>2</sup> )	PFAC
3.5	.538	1796	1.91
3.0	.461	2095	2.22
2.5	.385	2514	2.67

Once the required burning rate ( $\dot{r}$ ) is determined, appropriate values of  $a$  and  $n$  are required for the expression  $\dot{r} = a P_C^n$ .

The grain design problem is to find a geometry which will satisfy Table 5, together with the required conditions on  $L$ ,  $D$ ,  $P_C$ - $t$  and  $F$ - $t$  (and stress).

In the present program, only radially spoked star grains can be analyzed. It may not be possible to satisfy the motor requirements with this type of grain. The process is essentially one of trial-and-error.

Three attempts at meeting the design requirements are presented. One 6-point and two 8-point designs were tried.

A typical output from the "Design Mode" of "GRAINS" is shown in Table 6.

Once the "GRAINS Design Mode" has been run, "GRAINS Burnback" is run to obtain  $A_b$  versus web.

The output from "Burnback" for Case II is shown in Table 7.

"ROCKET" can then be run to obtain the pressure-time and thrust-time profiles. Input data for Case II are shown in Table 8.

A small section of the output from "ROCKET" is shown in Table 9 for Case II.

A summary of the results for the three cases is presented in Table 10 and pressure-time traces are shown in Figure 7.

None of the cases attempted met the desired design values with sufficient accuracy. Further iterations may result in a better solution. However, the star design has considerable sliver with the resulting long tailoff. This section was presented in order to demonstrate the process required to obtain a final grain design.



TABLE 6

## OUTPUT FROM "DESIGN MODE" OF "GRAINS"

## Design Inputs

Maximum Number of Spokes = 8      Grain Outer Radius = 8.00000  
 Desired Port Area = 43.89293      Desired Perimeter Factor = 2.48915  
 RI1 = 3.50000      DEL2 = -0.25000      FIN2 = 2.00000  
 SRI1 = 0.25000      DEL1 = 0.10000      FIN1 = 0.25000  
 SRI2 = 0.25000      DEL4 = 0.10000      FIN4 = 0.25000  
 FINWEB = 4.00000      WEBSTP = 0.25000      KSPOKE = 0.50000  
 CIRTOL = 0.10000      PTTOL = 0.10000      PERTOL = 0.10000

## Tolerance Limits

Port Area: Minimum = 39.50364      Maximum = 48.28222  
 Perimeter: Minimum = 52.61331      Maximum = 64.30515  
 Circle : Minimum = 324.00000      Maximum = 396.00000

Web Thickness = 2.5000

	A	APORT	PERIM	PFAC	RR1	R2	R3	R4	RR5	SR1	SR2	SPKT	PHI1	PHI2	PHI3	PHI4
ERROR ->	G1	greater	than	PTTOL,	therefore	equal										
8	51.692	53.535	2.100	3.500	3.750	5.250	5.500	8.000	0.250	0.250	3.107	3.823	26.814	2.729	5.082	
8	48.879	55.185	2.314	3.250	3.500	5.250	5.500	8.000	0.250	0.250	3.154	4.095	26.814	2.729	4.835	III
8	42.122	58.737	2.553	3.000	3.250	5.250	5.500	8.000	0.250	0.250	3.201	4.412	26.814	2.729	3.813	II
ERROR ->	G1	greater	than	PTTOL,	therefore	equal										
8	37.377	61.222	2.625	2.750	3.000	5.250	5.500	8.000	0.250	0.250	3.274	4.780	26.814	2.729	3.166	
ERROR ->	G1	greater	than	PTTOL,	therefore	equal										
9	32.581	63.602	3.143	2.500	2.750	5.250	5.500	8.000	0.250	0.250	3.349	5.216	26.814	2.729	2.295	
ERROR ->	G1	greater	than	PTTOL,	therefore	equal										
ERROR ->	G2	greater	than	PERTOL,	therefore	equal										
6	27.651	65.844	3.532	2.250	2.500	5.250	5.500	8.000	0.250	0.250	3.440	5.735	26.814	2.729	1.248	
ERROR ->	Phi4:	[	0.0]	less	than	0.0										
Spokes: 6    Phi1: 0.1    Phi2: 0.5    Phi3: 0.0																



TABLE 6 (CONTINUED)

OUTPUT FROM "DESIGN MODE" OF "GRAINS"

Web Thickness = 2.7500

N	APORT	PERIM	PFAC	RR1	R2	R3	R4	RR5	SR1	SR2	SPKT	PHI1	PHI2	PHI3	PHI4
ERROR -> R2 greater than PERTOL, therefore equal.															
8	45.465	48.191	2.016	3.500	3.750	5.000	5.250	6.000	0.250	0.250	3.287	3.323	30.769	2.666	0.634
ERROR -> R2 greater than PERTOL, therefore equal															
8	40.285	50.705	2.254	3.250	3.500	5.000	5.250	6.000	0.250	1.250	3.332	4.096	30.769	2.666	0.267
ERROR -> Phi4:1 0.03 less than 0.0															
Spokes: 8 Phi1: 0.1 Phi2: 0.5 Phi3: 0.1															
ERROR -> Phi4:1 0.01 less than 0.0															
Spokes: 8 Phi1: 0.1 Phi2: 0.5 Phi3: 0.1															
ERROR -> Phi4:1 0.01 less than 0.0															
Spokes: 8 Phi1: 0.1 Phi2: 0.5 Phi3: 0.1															
ERROR -> Phi4:1 -0.13 less than 0.0															
Spokes: 8 Phi1: 0.1 Phi2: 0.5 Phi3: 0.1															
ERROR -> Phi4:1 -0.11 less than 0.0															
Spokes: 8 Phi1: 0.1 Phi2: 0.5 Phi3: 0.1															

TABLE 7

## GRAINS "BURNBACK" OUTPUT FOR CASE II

## Design Inputs

Maximum Number of Spokes = 0      Grain Outer Radius = 8.00000  
 Desired Port Area = 42.12200      Desired Perimeter Factor = 2.55300  
 RI1 = 3.00000      DEL2 = 0.00000      FIN2 = 0.00000  
 SRI1 = 0.25000      DEL1 = 0.00000      FIN1 = 0.25000  
 SRI2 = 0.25000      DEL4 = 0.00000      FIN4 = 0.25000  
 FINWEB = 0.00000      WEBSTP = 0.00000      KSPKE = 0.00000  
 CIRTOL = 0.00000      PTTOL = 0.00000      PERTOL = 0.00000

## Burnback Inputs

Grain Length = 40.00000      PHI2 = 26.91400      PHI4 = 3.90600  
 STEP1 = 5.      STEP2 = 5.      STEP3 = 5.      STEP4 = 5.      STEP5 = 5.

Number of Spokes = 8.

Web Thickness = 2.50000

Web Burned (IN)	Perimeter (IN)	Perimeter Factor	Burn Area (SQ IN)	Port Area (SQ IN)
-----------------------	-------------------	---------------------	-------------------------	-------------------------

## Burnback of SR1 (Spoke Corner Radius)

0.000	58.737	2.553	2349.472	42.121
0.050	59.051	2.481	2362.038	45.066
0.100	59.365	2.416	2374.604	48.027
0.150	59.679	2.357	2387.170	51.003
0.200	59.993	2.303	2399.737	53.994
0.250	60.308	2.253	2412.303	57.002
0.250	60.308	2.253	2412.303	57.002
0.465	61.389	2.054	2455.576	71.054
0.679	62.150	1.904	2485.997	84.747
0.894	62.589	1.784	2503.564	97.978
1.108	62.707	1.682	2508.279	110.643
1.323	62.504	1.592	2500.141	122.639

TABLE 7 (CONTINUED)

GRAINS "BURNBACK" OUTPUT FOR CASE II

Burnback of LSPCKE (Booke Side)

1.323	62.504	1.578	2500.141	124.856
1.395	60.810	1.511	2432.411	128.918
1.468	59.117	1.447	2364.680	132.817
1.540	57.424	1.386	2296.950	136.593
1.613	55.730	1.328	2229.220	140.247
1.686	54.037	1.271	2161.489	143.777

Burnback of remainder to WEB = 0

1.686	54.037	1.271	2161.489	143.777
1.848	52.036	1.189	2061.455	152.320
2.011	51.533	1.146	2061.309	160.605
2.174	51.566	1.119	2063.440	169.198
2.337	51.930	1.099	2077.196	177.625
2.500	52.449	1.085	2097.974	186.124

Zero Web Thickness

Percent of fuel remaining = 9.40

Burnback of remaining fuel

2.832	20.320	0.409	612.798	196.073
2.943	15.430	0.309	617.194	195.051
3.066	10.419	0.208	418.756	199.637
3.200	5.278	0.105	211.107	200.683
3.343	0.000	0.000	0.000	201.055

# TABLE 8

## INPUT DATA FOR "ROCKET", CASE II

Motor Performance Program IBM-70 version 1.0  
INPUT DATA...

MOTOR HAS 1 GRAINS  
DESCRIPTION OF GRAIN 1

BURN RATE	0.3846
BURN RATE EXP.	0.4000
PI SUB K	0.2000
BURN REF. PRESS.	1030.2
C STAR	4768.0
C STAR EXP.	0.0081
DENSITY	0.0636
IGNITION TIME	0.0000
DELTA IGN. TIME	0.0000

Normal input is finished

General Configuration PARAMETERS are ...

Throat AREA	3.8510
Exit AREA	117.2903
Expansion RATIO	13.2517
Total Motor VOLUME	8042.5
AMBIENT Temperature	70.0
AMBIENT Pressure	10.1
Closure BLOWOUT	35.0
Pzero	15.0
Lambda	1.0000
Cd	0.9246
Gamma	1.1952
Throat DESIGN Pressur	1030.2
THROAT EROS. DELAY TI	2000.000

PRESSURE VS. THROAT EROSION RATE

600.	0.000000
1400.	0.000000

WEB	BURN AREA
0.000	2349.472
0.250	2411.952
1.108	2507.744
1.540	2296.212
2.011	2060.360
2.500	2097.107
2.832	812.473
3.342	0.000

TOTAL PROPELLANT WEIGHT=	411.996	IGNITER WEIGHT=	0.00
--------------------------	---------	-----------------	------

TABLE 9

## SAMPLE OUTPUT FROM "ROCKET", CASE II

TIME	PC	PDOT	FREE VOL	P WEIGHT	WDOTP	INS W	WDOT	AT	AVAL
7.205	585.14	-655.13	7533.15	379.60	33.81	0.00	35.12	8.851	0.0000
7.225	572.85	-645.45	7543.90	380.28	33.04	0.00	34.33	8.851	0.0000
7.246	559.73	-634.70	7554.42	380.95	32.27	0.00	33.55	8.851	0.0000
7.266	546.85	-624.11	7564.68	381.60	31.52	0.00	32.78	8.851	0.0000
7.287	534.18	-613.15	7574.71	382.24	30.78	0.00	32.03	8.851	0.0000
7.307	521.73	-602.31	7584.50	382.86	30.06	0.00	31.28	8.851	0.0000
7.327	509.51	-591.39	7594.07	383.47	29.35	0.00	30.56	8.851	0.0000
7.348	497.51	-580.60	7603.40	384.07	28.65	0.00	29.84	8.851	0.0000
7.368	485.73	-569.85	7612.51	384.65	27.97	0.00	29.14	8.851	0.0000
7.389	474.17	-559.22	7621.41	385.21	27.30	0.00	28.45	8.851	0.0000
7.409	462.82	-548.69	7630.09	385.75	26.64	0.00	27.77	8.851	0.0000
7.430	451.69	-538.30	7638.56	386.30	25.99	0.00	27.11	8.851	0.0000
7.450	440.77	-528.02	7646.83	386.83	25.35	0.00	26.46	8.851	0.0000
7.471	430.06	-517.90	7654.89	387.34	24.74	0.00	25.82	8.851	0.0000
7.491	419.56	-507.88	7662.76	387.84	24.13	0.00	25.19	8.851	0.0000
7.512	409.26	-498.04	7670.43	388.33	23.53	0.00	24.58	8.851	0.0000
7.532	399.16	-488.28	7677.91	388.81	22.95	0.00	23.97	8.851	0.0000
7.573	379.55	-469.21	7692.32	389.72	21.81	0.00	22.80	8.851	0.0000
7.614	360.71	-450.70	7706.01	390.59	20.72	0.00	21.68	8.851	0.0000
7.655	342.62	-432.72	7719.01	391.42	19.68	0.00	20.60	8.851	0.0000
7.696	325.25	-415.26	7731.35	392.21	18.67	0.00	19.56	8.851	0.0000
7.737	308.59	-398.32	7743.06	392.95	17.71	0.00	18.56	8.851	0.0000
7.778	292.52	-381.89	7754.16	393.56	16.78	0.00	17.61	8.851	0.0000
7.819	277.30	-365.96	7764.68	394.33	15.90	0.00	16.69	8.851	0.0000
7.860	262.63	-350.52	7774.64	394.96	15.05	0.00	15.81	8.851	0.0000
7.901	248.58	-335.56	7784.07	395.56	14.24	0.00	14.97	8.851	0.0000
7.942	235.13	-321.08	7792.99	396.13	13.47	0.00	14.17	8.851	0.0000
7.983	222.27	-307.06	7801.42	396.66	12.72	0.00	13.40	8.851	0.0000
8.024	209.97	-293.50	7809.38	397.17	12.01	0.00	12.66	8.851	0.0000
8.065	198.22	-280.38	7816.90	397.65	11.34	0.00	11.96	8.851	0.0000
8.106	186.99	-267.70	7823.99	398.10	10.69	0.00	11.28	8.851	0.0000
8.147	176.28	-255.44	7830.67	398.52	10.07	0.00	10.64	8.851	0.0000
8.188	166.21	-221.51	7836.97	398.92	9.54	0.00	10.04	8.851	0.0000
8.249	155.54	-138.62	7845.96	399.50	9.09	0.00	9.40	8.851	0.0000
8.341	145.01	-98.55	7852.72	400.31	8.55	0.00	8.76	8.851	0.0000
8.464	133.96	-84.16	7874.60	401.32	7.91	0.00	8.10	8.851	0.0000
8.628	120.86	-76.13	7893.98	402.55	7.14	0.00	7.31	8.851	0.0000
8.792	108.87	-69.82	7911.45	403.66	6.43	0.00	6.53	8.851	0.0000
8.956	97.89	-64.30	7927.17	404.66	5.78	0.00	5.93	8.851	0.0000
9.119	87.79	-58.96	7941.29	405.56	5.19	0.00	5.32	8.851	0.0000
9.324	76.36	-52.70	7956.89	406.55	4.51	0.00	4.63	8.851	0.0000
9.529	66.16	-47.05	7970.42	407.41	3.91	0.00	4.02	8.851	0.0000
9.775	55.39	-40.66	7984.27	408.30	3.27	0.00	3.37	8.851	0.0000
10.062	44.65	-34.30	7997.55	409.14	2.64	0.00	2.72	8.851	0.0000
10.389	34.48	-27.91	8009.53	409.90	2.04	0.00	2.10	8.851	0.0000
10.799	24.48	-21.16	8020.66	410.61	1.45	0.00	1.50	8.851	0.0000
11.311	15.62	-11.34	8030.00	411.20	0.91	0.00	0.94	8.851	0.0000



TABLE 9 (CONTINUED)

## SAMPLE OUTPUT FROM "ROCKET", CASE II

AVERAGE PRESSURE FROM MAXIMUM PRESSURE WAS				0.000 SEC. TO 1017.2 PSI		0.000 SEC. WAS		0.0 PSI	
TIME	PC	PE	F	INT PC	INT F	WEIGHT	CF	WT EXH	ISP
7.573	379.55	3.33	4368.49	6506.01	86251.34	389.72	1.300	389.90	221.78
7.614	360.71	3.30	4111.61	6521.17	86425.01	390.59	1.288	389.81	221.71
7.655	342.62	3.34	3873.89	6535.58	86588.55	391.42	1.277	390.57	221.64
7.696	325.25	3.37	3646.54	6549.25	86742.58	392.21	1.267	391.50	221.57
7.737	308.59	3.41	3429.23	6562.24	86887.49	392.95	1.256	392.28	221.49
7.778	292.62	3.45	3221.64	6574.55	87023.70	393.66	1.244	393.02	221.42
7.819	277.30	3.46	3023.47	6586.22	87151.60	394.33	1.232	393.72	221.35
7.860	262.63	3.52	2834.40	6597.29	87271.57	394.96	1.219	394.38	221.28
7.901	248.58	3.55	2654.13	6607.75	87383.98	395.56	1.206	395.02	221.22
7.942	235.13	3.60	2482.38	6617.65	87486.17	396.13	1.193	395.61	221.15
7.983	222.27	3.64	2328.52	6627.02	87587.70	396.66	1.184	396.18	221.08
8.024	209.97	3.68	2183.17	6635.87	87680.10	397.17	1.175	396.71	221.02
8.065	198.22	3.72	2044.55	6644.23	87766.70	397.65	1.166	397.22	220.95
8.106	186.99	3.77	1913.34	6652.12	87847.76	398.10	1.156	397.69	220.89
8.147	176.28	3.81	1788.37	6659.56	87923.57	398.52	1.146	398.14	220.84
8.188	166.21	3.86	1671.44	6666.59	87994.43	398.92	1.136	398.56	220.79
8.249	155.54	3.91	1548.13	6673.45	88063.34	399.50	1.125	399.16	220.70
8.341	145.01	3.96	1427.11	6680.31	88230.45	400.31	1.112	400.00	220.58
8.464	133.95	4.03	1300.94	6707.45	88355.05	401.32	1.097	401.03	220.43
8.628	120.86	4.11	1152.50	6728.22	88593.04	402.55	1.077	402.30	220.23
8.762	108.87	4.20	1017.93	6747.14	88776.84	403.66	1.055	403.44	220.05
8.956	97.53	4.29	895.70	6764.08	88933.61	404.68	1.034	404.46	219.88
9.119	87.79	4.36	784.56	6773.29	89071.26	405.56	1.010	405.38	219.72
9.324	78.36	4.51	669.20	6796.10	89219.20	406.55	0.977	406.40	219.53
9.529	68.16	4.64	550.76	6810.70	89343.21	407.41	0.941	407.23	219.36
9.775	55.39	4.81	437.17	6825.63	89464.61	408.30	0.892	408.20	219.17
10.062	44.65	5.02	326.18	6839.98	89574.05	409.14	0.825	409.07	218.97
10.389	34.48	5.28	224.00	6852.94	89664.13	409.90	0.734	409.85	218.77
10.799	24.48	5.66	126.70	6865.02	89735.01	410.61	0.585	410.60	218.55
11.311	15.62	6.19	43.51	6875.28	89779.58	411.20	0.315	411.21	218.33



TABLE 10

SUMMARY OF RESULTS FOR THREE GRAIN DESIGNS  
 $D = 16 \text{ IN}$ ,  $L = 40 \text{ IN}$

GRAIN 3	I	II	III
No. of pts.	6	8	8
web, in	2.5	2.5	2.5
Required $\dot{r}$ (in/sec)	0.385	0.385	0.385
P.F.	2.218	2.553	2.314
Port Area, in <sup>2</sup>	42.48	42.12	46.88
RR1, in	2.750	3.0	3.25
$\phi_2$	26.81	26.81	26.81
$\phi_4$	10.03	3.90	4.54
SR1, in	0.5	0.25	0.25
SR2, in	0.25	0.25	0.25
$P_{\max}$ , psia	990.	1,017.	952.
$F_{\max} \text{ lb}_f$	12,464.	13,702.	12,749.
$\bar{F} \text{ lb}_f$	6,956.	7,945.	7,738.
$I_T$ , $\text{lb}_f\text{-sec}$	91,151.	89,780.	87,690.
$t_{\text{burn total}}$ , sec	13.1	11.3	11.2

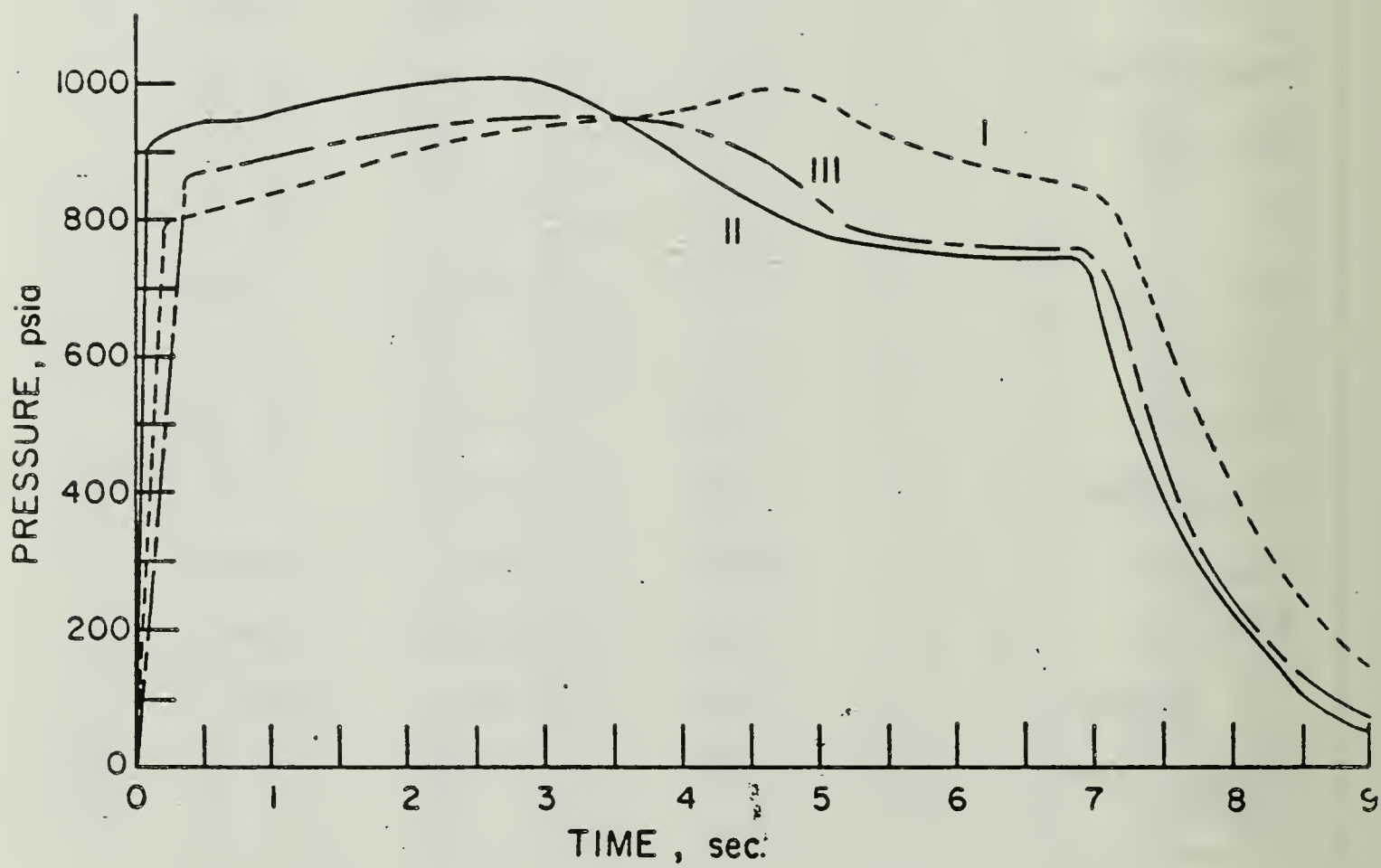


FIGURE 7.

PRESSURE-TIME PROFILES FROM "ROCKET"

## X. CONCLUSIONS AND RECOMMENDATIONS

### A. CONCLUSIONS

An interactive computer code for the preliminary design of solid rocket propellant rocket motors ("SPRMD") was successfully developed and its use was demonstrated through a design example. The code incorporated several existing PC codes and AGARD recommended empirical expressions for losses in aluminized propellant systems.

### B. RECOMMENDATIONS

Further modifications to improve the capabilities of the code are essential in order to make "SPRMD" a more effective preliminary design tool.

- There is only one grain configuration (radially spoked star grains) incorporated into "SPRMD."

It is necessary to add other options for grain design in order to increase the grain design flexibility. One possibility would be to incorporate the Grain Design and Internal Ballistics (GDB) module of Solid Performance Prediction Code (SPP) (Ref. 3).

- "SPRMD" also does not currently incorporate any plotting capabilities. There is definitely a need for this program to have plotting capabilities for the grain design results and the thrust and pressure versus time profiles.

- "FLYIT" was not incorporated into the program, although "SPRMD" was structured to have flight simulation capabilities. It is also recommended that "FLYIT" be incorporated into "SPRMD" as another enhancement.
- "SPRMD" is a primitive type of preliminary solid propellant rocket motor design code. Further enhancements, such as propellant searching, screen editing, and increased solution speed for "MICROPEP" and "ROCKET" would make this code more user friendly.

# APPENDIX

```

      program SPRMD.
C*****
C
C SOLID PROPELLANT ROCKET MOTOR DESIGN
C THIS PROGRAM (SPRMD) SOLVE THE PRELIMINARY DESIGN PROBLEM*
C OF SOLID PROPELLANT ROCKET MOTOR. SUBROUTINES INCLUDES: *
C (1) INPUT0: BASIC INPUT FOR DESIGN
C (2) INPUT1: CHEMICAL COMPOSITION INPUT
C (3) MICROPEP: PERFORME THE PROPELLANT EVALUTION
C (4) PFE: SIZE THE THROAT OF NOZZLE PORT AREA OF GRAIN ETC*
C (5) LOSCF: CALCULATE THE THRUST COEFFICIENT
C (6) INPUT2: STAR GRAIN INPUT
C (7) GRAINS: PERFORM THE SPOKED STAR GRAINS DESIGN
C (8) RCKTIN: INPUT THE DATA FOR THRUST AND PRESSURE PRO- *
C          FILE CALCULATION
C (9) ROCKET: COMPUTED THE THRUST AND PRESSURE PROFILE
C*****
C
      real favg,tb,l,d,meop,pc,rrqd,pamb,tamb,h,ld,webrqd,wf,m
      common /micrp/ a(12,12),kr(20),amat(10,12),jat(12),in,is,
      lfie(10,6),ie(10,6),alp(12),w27,n,dh(10),rho(10),
      2wate(10),wl(6),w43,ig,np,vnt(201),w47,name,ser,
      3floor,itag(100),wing(10)
C      integer
C      character*10 yes
C*****
C
C BASIC INPUT FOR MOTOR DESIGN
C
C*****
1000 call input0(favg,tb,l,d,meop,pc,rrqd,pamb,tamb,h,fmin,tpmax,tpnom,
      *tpmin,pik)
      write(*,1) favg
1    format(1x,'AVERAGE THRUST, LBF..... ',f12.1)
      write(*,2) tb
2    format(1x,'BURN TIME, SEC..... ',f12.2)
      write(*,12) fmin
12   format(1x,'MINIMUM THRUST REQUIRED, LBF..... ',f12.6)
      write(*,3) l
3    format(1x,'MOTOR LENGTH, INCH..... ',f12.2)
      write(*,4) d
4    format(1x,'MOTOR DIAMETER, INCH..... ',f12.2)
      write(*,5) meop
5    format(1x,'MAXIMUM EXPECTED OPERATING PRESSURE... ',f12.1)
      write(*,13) tpmax
13   format(1x,'TPMAX, F..... ',f12.1)
      write(*,131) tpnom
131  format(1x,'TPNOM, F..... ',f12.1)
      write(*,132) tpmin
132  format(1x,'TPMIN, F..... ',f12.1)
      write(*,14) pik
14   format(1x,'TEMPERATURE SENSITIVITY, %/F..... ',f12.3)
      write(*,6) pc
6    format(1x,'NOMINAL CHAMBER PRESSURE, PSI..... ',f12.1)
      write(*,7) rrqd
7    format(1x,'REQUIRED BURNING RATE, IN/SEC..... ',f12.3)
      write(*,8) h
8    format(1x,'ALTITUDE, FT..... ',f12.0)
      write(*,9) pamb
9    format(1x,'AMBIENT PRESSURE, PSI..... ',f12.2)

```



# APPENDIX

```

        write(*,11)tamb
11  format(1x,'AMBIENT TEMPERATURE, R.....',f12.1)
    write(*,10)
10  format(1x,'ANY CORRECTION OF BASIC INPUT? Y-YES, N-NO... ')
    read(*,20)yes
20  format(a10)
    if(yes.eq.'y'.or.yes.eq.'Y') go to 1000
C
C*****
C
C INPUT THE DATA NEEDED BY MICROPEP
C
C*****
C
C
1010 call input1(pc,pamb)
    write(*,40)
40  format(1x,'Are there any corrections of input for micropep?,y-yes
    *n-no ')
    read(*,20)yes
    if(yes.eq.'Y'.or.yes.eq.'y') go to 1010
C
C*****
C
C COMPUTE THERMAL EQUILIBRIUM, PROPELLANT CHARACTERISTIC,
C AND ETC.(USING MICROPEP, UNTILL GOOD RESULTS ARE REACHED)*
C
C*****
C
    call micropep
    write(*,50)
50  format(1x,'Are the results good? y-yes n-no ')
    read(*,20)yes
    if(yes.eq.'y'.or.yes.eq.'Y') then
        go to 1020
    else
55  write(*,60)
60  format(1x,'(1) Change the Basic Inputs of motor.').
    write(*,70)
70  format(1x,'(2) Change the Input data for Micropep.').
    write(*,80)
80  format(1x,' type 1, or 2, if 1 is chosen it is necessary')
    write(*,90)
90  format(1x,' that Micropep shall be run once again!!!!')
    read(*,100)i
100 format(i1)
    if(i.ne.1.and.i.ne.2) then
        write(*,*)' Error input!! 1, or 2 must be typed'
        go to 55
    else
        if(i.eq.1) go to 1000
        if(i.eq.2) go to 1010
    endif
    endif
C*****
C
C CALCULATE THE LOSS PERFORMANCE & COMPUTE THE DATA FOR
C GRAIN DESIGN
C
C*****

```



# APPENDIX

```

C
1020 call pfe(favg,tb,1,d,pc,cfc,ath,etacf,m,vp,vl,dpe,aport,
*pfac,isp,cfth,webrqd,wf,tc,rrqd,ae,etac,xx)
    write(*,50)
    read(*,20)yes
    if(yes.eq.'y'.or.yes.eq.'Y') then
        go to 1030
    else
        75 write(*,60)
            write(*,70)
            write(*,71)
        71 format(1x,'(3) Change nozzle data.')
            write(*,72)
        72 format(1x,' type 1, 2, or 3 ')
            read(*,100)i
            if(i.lt.1.and.i.gt.3) then
                write(*,*)'Error input!! 1, 2 or 3 must be typed'
                go to 75
            else
                if(i.eq.1) go to 1000
                if(i.eq.2) go to 1010
                if(i.eq.3) go to 1020
            endif
        endif
    endif
C*****
C
C CHOOSE THE APPROPRIATE GRAIN DESIGN
C NOTE: OPTION 2, 3, 4, 5, 6, 7 ARE NOT AVAILABLE. INPUT
C YOUR OWN DESIGN BY SUBSTITUTE THE WRITE AND GOTO STATE-
C MENTS IN THE CORRESPONDING BLOCK
C
C*****
1030 write(*,110)
110 format(1x,'Choose one of the following grain configurations')
    write(*,120)
120 format(1x,'(1) Star grain')
    write(*,130)
130 format(1x,'(2) Optional grain ')
    write(*,140)
140 format(1x,'(3) Optional grain ')
    write(*,150)
150 format(1x,'(4) Optional grain ')
    write(*,160)
160 format(1x,'(5) Optional grain ')
    write(*,170)
170 format(1x,'(6) Optional grain ')
    write(*,180)
180 format(1x,'(7) Optional grain ')
    write(*,190)
190 format(1x,'Type 1, 2, 3, .....etc.')
    read(*,*)i
    if(i.lt.1.or.i.gt.7) then
        write(*,200)
        200 format(1x,'Error input!! must type 1, 2, 3,.....,7')
            go to 1030
    else
        if(i.eq.1) then
            rr5=d/2.0
            write(*,*)'Run "DESIGN MODE" '
        1050 call input2(pfac,aport,webrqd,rr5,1,tb,xx)

```

# APPENDIX

```

    call grains
    write(*,*) 'Are the results are acceptable? y-acceptable n-not
*acceptable type y or n..'
    read(*,20)yes
    if(yes.eq.'n'.or.yes.eq.'N') then
        go to 1050
    else
        go to 1055
    endif
1055 rr5=d/2.0
    write(*,*) 'Run the "BURNBACK MODE" to get web vs. burning area'
    call input2(pfac,aport,webrqd,rr5,1,tb,xx)
    call grains
    write(*,*) 'Are the results are acceptable? y-acceptable n-not
*acceptable type y or n..'
    read(*,20)yes
    if(yes.eq.'n'.or.yes.eq.'N') then
        write(*,*) 'Do you want to try another star grain? y/n '
        read(*,20)yes
        if(yes.eq.'n'.or.yes.eq.'N') then
            go to 1030
        else
            go to 1050
        endif
    else
        go to 1060
    endif
else
    if(i.eq.2) then
        write(*,280)
280     format(lx,'Input your own grain design package')
        go to 1030
    else
        if(i.eq.3) then
            write(*,290)
290     format(lx,'Input your own grain design package')
            go to 1030
        else
            if(i.eq.4) then
                write(*,300)
300     format(lx,'Input your own grain design package')
                goto 1030
            else
                if(i.eq.5) then
                    write(*,310)
310     format(lx,'Input your own grain design package')
                    go to 1030
                else
                    if(i.eq.6) then
                        write(*,320)
320     format(lx,'Input your own grain design package')
                        go to 1030
                    else
                        if(i.eq.7) then
                            write(*,330)
330     format(lx,'Input your own grain design package')
                            go to 1030
                        endif
                    endif
                endif
            endif
        endif
    endif

```

# APPENDIX

```

        endif
    endif
endif
endif
endif
c
c*****
c
c INPUT THE DATA FOR THRUST & PRESSURE VERSUS TIME PROFILE*
c CALCULATION
c
c*****
1060 write(*,*)'The following processes is to calculate the "THRUST VS.
    * TIME" and "PRESSURE VS. TIME" profiles'
    va=(d/2.0)**2.0*3.14159*1
    rrqd=webrrqd/tb
    write(*,106)rrqd
106 format(1x,'Required burning rate for new web, IN/SEC.. ',f6.4)
1070 call rcktin(ath,ae,va,tamb,pamb,pc,etacf,rrqd,pik,etac)
    write(*,*)'Any change for the input? y=yes, n=no '
    read(*,20)yes
    if(yes.eq.'y'.or.yes.eq.'Y') then
        go to 1070
    else
        go to 1080
    endif
c
c*****
c
c COMPUTE THE PRESSURE VS. TIME & THRUST VS.TIME PROFILE *
c OF ROCKET MOTOR
c
c*****
c
1080 call rocket
c
    write(*,340)
340 format(1x,'Are the results acceptable? y-yse, n-no.....')
    read(*,20)yes
    if(yes.eq.'y'.or.yes.eq.'Y')then
        go to 9999
    endif
    write(*,350)
350 format(1x,'Do you want to proceed? y=yes, n-no.....')
    read(*,20)yes
    if(yes.eq.'N'.or.yes.eq.'n') then
        write(*,*)'Terminated on the request of user '
        go to 9999
    endif
1040 write(*,360)
360 format(1x,'Suggest to change the following data')
    write(*,380)
380 format(1x,'(1) Change the Grain Design.')
    write(*,390)
390 format(1x,'(2) Change the Ingredients of the propellant.')
    write(*,400)
400 format(1x,'(3) Change the Basic Design Requirements.')
    write(*,*)'(4) Re-run the "ROCKET"'
    write(*,*)' Type 1, 2 or 3 for selection'
    read(*,100)i

```

# APPENDIX

```

if(i.ne.1.and.i.ne.2.and.i.ne.3) then
  write(*,*)' Error input you have to type 1, 2 or 3'
  go to 1040
else
  if(i.eq.1) then
    go to 1030
  else
    if(i.eq.2) then
      go to 1010
    else
      if(i.eq.3) then
        go to 1000
      else
        if(i.eq.4) go to 1070
      endif
    endif
  endif
endif
endif
C*****
C
C INPUT THE TRAJECTORY DATA (FUTURE WORK)
C
C*****
C
C      call flyin
C
C*****
C
C CALCULATE THE TRAJECTORY OF ROCKET MOTOR (FUTURE WORK)
C
C*****
C
C      call flyit
9999 end

```



# APPENDIX

```

      subroutine Input0(favg,tb,l,d,meop,pc,r,pamb,tamb,h,fmin,tpmax,
      *tpnom,tpmin,pik)
c*****
c
c THIS SUBROUTINE IS FUNCTION AS A BASIC INPUT FOR SOLID
c PROPELLANT ROCKET MOTOR DESIGN
c
c*****
c
c variable definition:
c ***** (ballistic performance) *****
c   favg      : average thrust (F12.6)
c   tb        : burning time of motor (F12.6)
c   fmin      : minimum thrust (F12.6)
c   ***** (mission/vehicle) *****
c   l         : motor length (F12.6)
c   d         : motor diameter (F12.6)
c   meop      : maximum expected operating pressure (F12.6)
c   va        : motor volume available for propellant (F12.6)
c   tpmax, tpnom, tpmin
c   pmaxtp    : meop * (1-reproducibility tolerance) (F12.6)
c   pc        : nominal chamber pressure (F12.6)
c   rptol     : reproducibility tolerance (F12.6)
c   r         : burning rate (F12.6)
c   web       : web of grain (F12.6)
c   pik       : temperature sensitivity of propellant(F12.6)
c   h         : altitude(F12.6)
c   real favg,tb,fmin,l,d,meop,va,dltp,pmaxtp,pc,rptol,r,web,h
c   open a file which can hold the basic input data
c   open(2,file='input0.dat',access='sequential',status='unknown')
c   input basic data
c   write(*,*)'All input data in decimal format'
c   write(*,*)'Specify the average thrust, LBF..... '
10  read(*,10)favg
   format(f12.6)
   write(2,10)favg
c   write(*,*)'Input burning time of motor, SEC..... '
   read(*,10)tb
   write(2,10)tb
c   write(*,*)'Input minimum thrust required, LB..... '
   read(*,10)fmin
   write(*,*)'Input motor length, INCHES..... '
   read(*,10)l
   write(2,10)l
c   write(*,*)'Input motor diameter, INCHES..... '
   read(*,10)d
   write(2,10)d
c   write(*,*)'Input maximum expected'
c   write(*,*)'operating pressure, PSI..... '
   read(*,10)meop
   write(2,10)meop
c   write(*,*)'Input Tpmax, F..... '
   read(*,10)tpmax
   write(2,10)tpmax
c   write(*,*)'Input Tpnom, F..... '
   read(*,10)tpnom
   write(2,10)tpnom
c   write(*,*)'Input Tpmin, F..... '
   read(*,10)tpmin
   write(2,10)tpmin

```



# APPENDIX

```

write(2,10)dltp
write(*,*)'Input reproducibility tolerance, %..... '
read(*,10)rptol
write(2,10)rptol
rptol=rptol/100.0
pmaxtp=meop*(1.0-rptol)
rptol=rptol*100.0
r=(d/4)/tb
write(*,20)r
write(2,10)r
20 format(1x,'Estimated repuired burn rate..... ',f12.3,
*' INCH/SEC')
write(*,30)
c The following calculation of ambient temperature and pressure at
c certain altitude is directly copied from NWC Technical Memorandum
c 4757 subroutine atmstd based on U.S Standard Atmosphere, 1976.
30 format(1x,'Input the required design altitude of rocket motor in F
*T
*')
read(*,10)h
write(2,10)h
if(h-36152.)1,1,2
1 tamb=518.67-0.003559969*h
ro=0.00237696*exp(-(0.028800339*(h*.001)+0.000132317*(h*.001)**2))
go to 7
2 if(h-65825.)3,3,4
3 tamb=389.97
ro=0.00237696*0.29697*exp(-0.04771923*(h-36152.)*.001)
go to 7
4 if(h-105511.)5,5,6
5 tamb=354.142+0.0005442926*h
ro=0.00237696*0.0718594*exp(-(0.049130937*(h-64825.)*.001
&-0.000034655*((h-65825.)*.001)**2))
go to 7
6 tamb=251.4114+0.00151794*h
ro=0.00237696*0.0107993*exp(-(h-105511.)/21320.)
7 pamb=11.9203*ro*tamb
write(2,10)pamb
write(2,10)tamb
c end of calculation of tempessure and temperature at design alt.
c
write(*,*)'Based on available requirements, make an initial'
write(*,*)'selection of propellant. Then input the temperature'
write(*,*)'sensitivty of the propellant, %/F..... '
read(*,40)pik
write(2,40)pik
40 format(f12.6)
pik=pik/100.0
pc=pmaxtp*exp(pik*(tpnom-tpmax))
pik=pik*100.0
write(2,10)pc
close(2,status='keep')
return
end

```

# APPENDIX

```

      subroutine input1(pc,pamb)
c*****
c
c THE PRIMARY PURPOSE OF THIS SUBROUTINE IS TO ESTABLISH
c THE DATA FILE WHICH CAN BE ACCESSED BY MICROPEP SUB-
c TIME
c
c*****
c
      common /micrp/ a(12,12),kr(20),amat(10,12),jat(12),in,is,fi(10,6)
      1,ie(10,6),alp(12),w27,n,dh(10),rho(10),wate(10),wl(6),w43,ig,np,
      2vnt(201),w47,name,ser,floor,itag(100),wing(10)
      common/chara/block,je,aspec,specie
      character*8 specie(200)
      character*30 block(10),ofile
      character*2 je(10,6),aspec(12)
      common/moon/tstest,te,irun,iounit,iend
      character*30 blok(10)
      character*10 user
      dimension jie(10,6)
      integer nic,niu,irun,alt,kr
      real denexp
c
c      open the file as formatted sequential as unit 3
      open(3,file='input.dat',access='sequential',status='unknown')
c      input the case name from the keyboard
      write(*,*)' Start to input the selected propellant data
      write(*,*)'
      write(*,1)
      1 format(1x,'Specify the case name (format A10)..... ')
      read(*,'(a)')user
      write(3,10)user
      10      format(1a10)
      irun=2
c      input the number of ingredients, supplied ingredients, and runs
      write(*,*)'Input the number of ingredients? (format I5)....'
      read(*,*)nic
      write(*,*)'Input the number of user supplied ingredients (I5)...'
      read(*,*)niu
      write(3,25)nic,niu,irun
      20      format(2i5)
      25      format(3i5)
c      Input density exponent which is used in conjunction with control
c      option 3.
      write(*,*)'Input the density exponent:'
      write(*,*)'For tactical missiles or first stages use 1.0'
      write(*,*)'Use 0.7 for second stages and 0.2 for third stages'
      write(*,*)'(format F10.0)..... '
      read(*,40)denexp
      write(3,40)denexp
      40      format(f10.5)
c
c      input control option store it in kr(20)
c      print out the options on the screen
      write(*,'(a)')'There are five options listed below for your'
      write(*,*)'selection. Type 1, 2, 3, 4, 5---'
      write(*,*)'Normal input for design is 3'
      write(*,'(a)')' 1. For chamber and exit calculations.'
      write(*,'(a)')' 2. For chamber only calulations.'
      write(*,'(a)')' 3. For boost performance and nozzle design.'

```

# APPENDIX

```

write(*,'(a)')' 4. For equilibrium calculations at specified T'
write(*,'(a)')' and P. Use T in Kelvin at Pe location and P'
write(*,'(a)')' in psia at the normal Pc location.'
write(*,'(a)')' 5. Other options ( Check README for special'
write(*,'(a)')' alternatives).'
write(*,*)'Use format I1 '
read(*,45)alt
45 format(i1)
   if (alt.lt.5) then
       kr(2) = 0
       kr(4) = 0
       kr(5) = 0
       kr(6) = 0
       kr(8) = 0
       if (alt.eq.1) then
           kr(1) = 0
           kr(3) = 0
           kr(7) = 0
       else
           if (alt.eq.2) then
               kr(1) = 1
               kr(3) = 0
               kr(7) = 0
           else
               if (alt.eq.3) then
                   kr(1) = 0
                   kr(3) = 1
                   kr(7) = 0
               else
                   kr(1) = 0
                   kr(3) = 0
                   kr(7) = 1
               endif
           endif
       endif
       endif
       write(3,50)(kr(i),i = 1,8)
50 format(8i1)
   else
       write(*,'(a)')' Input your requirements for calculation--'
       read(*,60)(kr(i),i = 1,15)
       write(3,60)(kr(i),i = 1,15)
60 format (15i1)
   endif
c   input the serial number of ingredients found in JANNAF.DAT table
c
   write(*,70) nic
70 format(lx,'Input ',i2,' ingredients needed for calculation')
   do 100 i = 1,nic
       write(*,80)i
80 format(lx,'Serial # of number ',i5,' ingredient(I5)... ')
       read(*,90)itag(i)
90 format(i5)
100 continue
       write (3,120)(itag(i), i = 1,nic)
120 format(10i5)
c   Input user supplied ingredients
   if (niu.gt.0) then
       do 170 i = 1,niu
           write(*,'(a)')'Specify ingredient name use caps lock (A30) '
           read(*,130)blok(i)

```

# APPENDIX

```

write(*,'(a)') 'Specify composition of ingredient max = 6'
write(*,'(a)') ' use (6(I3,A2))'
write(*,'(a)') ' #####'
read(*,140)(jie(i,1),je(i,1),l=1,6)
write(*,'(a)') ' Specify heat of formation, and density (f5.0,f6
*.0)
      read(*,150)dh(i),rho(i)
      write(3,160)blok(i),(jie(i,1),je(i,1),l=1,6),dh(i),rho(i)
130      format(a30)
140      format(6(i3,a2))
150      format(f5.0,f6.0)
160      format(a30,6(i3,a2),f5.0,f6.0)
170      continue
      else
        write (*,'(a)') ' No user supplied ingredients. '
      endif
      if (irun.lt.2) then
        irun = 2
      endif
      status=0
      do 220 i = 1,irun
        if(status.eq.0) then
          c      write (*,'(a)') ' Specify the desired chamber pressure (F12.4) '
          c      read (*,180)wl(5)
          wl(6)=pamb
          c      write (*,'(a)') ' Specify the exhaust pressure (F12.4)'
          c      read (*,190)wl(6)
          ni=nic+niu
          do 175 j =1,ni
            write(*,172)itag(j)
            172      format(1x,'Input the weight % of ingredient',i5,'(F10.4)...')
            read(*,190)wing(j)
            175      continue
            180      format(f10.4)
            190      format(f10.4)
            write(3,210)wl(5),wl(6),(wing(j),j=1,10)
            210      format(12f10.4)
            status=1
          else
            wl(5)=pc
            write(3,210)wl(5),wl(6),(wing(j),j=1,10)
          endif
          220      continue
          close(3)
          return
        end

```



# APPENDIX

```

      subroutine pfe(favg,tb,l,d,pc,cfc,ath,etacf,m,vp,vl,dpe,aport,
      +pfac,isp,cfth,webrqd,wf,tc,r,ae,etac,xx)
c*****
c
c THE MAIN PURPOSE OF THIS SUBROUTINE IS TO CALCULATE THE *
c PERFORMANCE LOSS AND THE DATA FOR GRAIN DESIGN *
c *
c*****
c variable definitions:
c   favg:      Average thrust from basic input
c   cfth:      thrust coefficient from micropep
c   cfc :      corrected cf
c   pc :      chamber pressure from basic input
c   d :      motor diameter from basic input
c   l :      motor length from basic input
c   athth:     theoretical throat area
c   ath :      throat area
c   atht :     tempory result of throat
c   dthth:     theoretical throat diameter
c   etacf:     thrust coefficient efficiency
c   dif :      for convergence test of throat size
c   va :      vol avaiable for propellant
c   tb :      burn time
c   vp :      propellant vol.
c   vl :      volumetric loading factor
c   aport:     port area
c   dpe :      equivalent circular port diameter
c   pwet :     wetted perimeter
c   j :      throat-to-port area ratio
c   rhop :     propellant mass density
c   mw :      molecular weight of propellant
c   mf :      mole fraction of condensed phase
c   webrqd:    required web
c   wf :      web fraction
c   pfac :     perimeter factor
c   character*80 fname
c
      real favg,cfth,cfc,pc,d,l,athth,ath,dthth,etacf,dif,tb,vp,vl,va,j,
      +aport,dpe,rhop,a,nn,rstd,rpc,web,webrqd,wf,m,pwet,pfac,isp,isp,at
      +ht,mw,tc,ispth,ld,mf
      character*1 yes
c The purpose of this common instruction is to transfer w43(propellant
c density) from MICROPEP: SUBROUTINE PUTIN(LE)
      common /micrp/ a(12,12),kr(20),amat(10,12),jat(12),in,is,
      lfie(10,6),ie(10,6),alp(12),w27,n,dh(10),rho(10),
      2wate(10),wl(6),w43,ig,np,vnt(201),w47,name,ser
      3,floor,itag(100),wing(10)
c The purpose of this common instruction is to transfer the CHAMBER PRE-
c SSURE & MOLECULAR WEIGHT from MICROPEP SUBROUTINE OUT.
      common /tcf/ tfc,rmwtc
c Transfer SPECIFIC IMPULSE, CHARACTERISTISC VEL., CODFF. OF THRUST &
c OPTIMUN EXPANSION RATIO from MICROPEP SUBROUTIN DESING.
      common /socf/ spi(2),cf(2),oex(2)
c calculate the theoretical throat area
      pi=3.14159
c transfer cfth from "MICROPEP"
      cfth=cf(2)
c initialize cfc
      cfc=cfth
      athth=favg/(cfth*pc)

```



# APPENDIX

```

c initialize ath=athth
ath=athth
c calculate theoretical throat diameter
dthth=sqrt(ath/pi)*2
write(*,888)cfth,athth,dthth
888 format(1x,'cfth=',f5.3,' Athth=',f6.3,' Dthth=',f5.3)
c calculate the etacf
write(*,*)'Input the nozzle half angle'
write(*,*)'alpha, DEGREES (F5.2).....'
read(*,*)alpha
pi=3.14159
alpha=(alpha/180.0)*pi
write(*,*)'Input the nozzle exit half angle'
write(*,*)'thetaex, DEGREES (F5.2).....'
read(*,*)thetaex
thetaex=(thetaex/180.0)*pi
write(*,*)'Input radial erosion rate of the throat in IN/SEC'
write(*,*)'assumed to start at time zero (FORMAT 0.XXXX)....'
read(*,*)erosr
write(*,*)'Input the mole fraction of condensed'
write(*,*)'phase in (MOLE/100 g).....'
read(*,*)mf
write(*,*)'Input the material of nozzle:'
write(*,*)'1-steel nozzle, 0-ordinary nozzle.....'
read(*,*)nozzle
atht=ath
do 9 i=1,50
C calculate the loss mechanism
call loscf(etacf,tb,ath,pc,alpha,thetaex,erosr,mf,nozzle)
c correct the trust coefficient
cfc=cfth*etacf
c calculate the corrected throat area
ath=favg/(cfc*pc)
write(*,8888)etacf,cfc,ath
8888 format(1x,'Etacf=',f12.3,' cfc=',f12.3,' Ath=',f12.3)
c calculate the convergence athth and ath
dif=abs((atht-ath)/atht)*100.0
if (dif.gt.1.0) then
atht=ath
else
go to 91
endif
9 continue
91 va=pi*(d/2)**2*1
etac=0.93
vol=pi*(d/4)**2*1
c Density and molecular weight com from "MICROPEP"
rhop=w43
mw=rmtc
tc=tfc
ispth=spi(2)
write(*,98)rhop,mw,tc,ispth
98 format(' Rhop=',f12.3,' MW=',f12.3,' Tc=',f12.1,' Ispth=',f12.2
*)
99 isp=ispth*etacf*etac
m=favg/isp
vp=favg*tb/(isp*rhop)
vl=vp/va
write(*,87)VP,VA,VL
87 format(' VP=',F12.1,' VA=',F12.1,' VL=',F12.3)

```

# APPENDIX

```

dpe=sqrt(1.0-v1)*d
aport=(pi/4)*d**2*(1-v1)
tres=(aport*1)*pc*mw/(m*12*1545*(tc+459.6))
tres=tres*1000.0
write(*,88)tres
88 format(' RESIDENCE TIME IN MSEC..... ',f12.3)
write(*,89)etac
89 format(' COMBUSTION EFFICIENCY (etac)..... ',f12.3)
write(*,*)'Change etac? y=yes, n-no..... '
read(*,20)yes
if(yes.ge.'y'.or.yes.eq.'Y') then
    write(*,*)'Input etac..... '
    read(*,30)etac
    vol=aport*1
    go to 99
endif
c calculate the nozzle exit area
ae=ath*oex(2)
c calculate the required perimeter factor
write(*,19)pc
19 format(1x,'Input the C* with Pcnom=',f10.1,' (F10.4)..... ')
read(*,*)cstar
xx=(pc*ath*32.17)/(cstar*rhop*1*3.14159*dpe)
18 write(*,*)'Input the estimated required web (INCHES) (F10.4)'
write(*,*)'suggest initial guess D/4..... '
read(*,*)webrqd
r=webrqd/tb
pfac=xx/r
write(*,21)r
21 format(1x,'The required burn rate =',f6.4)
write(*,22)pfac
22 format(1x,'The required perimeter factor=',f6.3)
write(*,25)xx
25 format(1x,'pfac=',f5.4,'/r')
write(*,24)tb
24 format(1x,'tb =',f7.2)
write(*,*)'Are these acceptable? y=yes n-no..... '
read(*,20)yes
if(yes.ge.'y'.or.yes.eq.'Y') then
    pwet=pfac*pi*dpe
    wf=webrqd/(d/2)
    j=ath/aport
    ld=1/d
    go to 23
else
    go to 18
endif
20 format(a1)
30 format(f12.6)
23 write(*,40)cfc
40 format(1x,'THRUST COEFFICIENT..... ',F12.3)
write(*,50)etacf
50 format(1x,'ETACF..... ',F12.3)
write(*,60)isp
60 format(1x,'SPECIFIC IMPULSE, LBF SEC/LBM..... ',f12.3)
write(*,70)m
70 format(1x,'MASS FLOW RATE, LBM/SEC..... ',f12.3)
write(*,80)vp
80 format(1x,'PROPELLANT VOLUME, CU IN..... ',f12.1)
write(*,100)ath

```

## APPENDIX

```

100  format(1x,'NOZZLE THROAT AREA, SQ IN.....',f12.3)
      write(*,105)ae
105  format(1x,'NOZZLE EXIT AREA,    SQ IN.....',f12.3)
      write(*,110)dpe
110  format(1x,'EQUIVALENT PORT DIAMETER, IN.....',f12.3)
      write(*,120)aport
120  format(1x,'PORT AREA, SQ IN .....',f12.3)
      write(*,130)pfac
130  format(1x,'PERIMETER FACTOR.....',f12.3)
      write(*,140)webrqd
140  format(1x,'REQUIRED WEB, IN.....',f12.3)
      write(*,150)wf
150  format(1x,'REQUIRED WEB FRACTION.....',f12.3)
      write(*,90)vl
90   format(1x,'VOLUMETRIC LOADING.....',f12.3)
      write(*,190)ld
190  format(1x,'LENGTH TO DIAMETER RATIO.....',f12.3)
      write(*,170)tres
170  format(1x,'RESIDENCE TIME, MSEC.....',f12.3)
      write(*,180)j
180  format(1x,'THROAT TO PORT AREA RATIO (J FACTOR)...',f12.3)
      write(*,200)r
200  format(1x,'REQUIRED BURNING RATE,    IN/SEC.....',f12.3)
      return
      end

```

# APPENDIX

```

      subroutine loscf(etacf,tb,ath,pc,alpha,thetaex,erosr,
      *mf,nozzle)
c*****
c
c THIS SUBROUTINE CALCULATE THE NOZZLE LOSS COEFFICIENT
c (THRUST COEFFICIENT) USING THE METHODS PROPOSED BY AGARD
c PROPULSION AND ENERGETICS PANEL FOR METALLIZED PRO-
c PELLANTS (Reference: Performance of Rocket with Metal-
c lized propellants, AGARD-AR-230)
c
c*****
c Defination of variables in this subroutine
c      etacf:    nozzle loss coefficient
c      div  :    percent divergence loss
c      kin  :    percent kinetics loss
c      bl   :    percent boundary layer loss
c      tp   :    percent two-phase loss
c      sub  :    persent submergence loss
c      eros :    percent nozzle erosion loss
c      astar:    nozzle entrance/ nozzle throat area
c      s    :    submergence length/ length of internal motor
c      mf   :    mole fraction of condensed phase in mole/100grm
c      c1,c2,c3,c4,c6 :
c                  constant in emperical relation
c      dp   :    diameter of particle
c      pc   :    chamber pressure
c      ispf :    Isp of frozen equilibrium
c      isps :    Isp of shifting equilibrium
c      nozzle:    steel nozzle = 1, ordinary nozzle = 0
c      tb   :    burning time of motor
c      dt   :    throat diameter
c      expn :    nozzle expansion ratio
c      ispi :    Isp with ideal (at design point) nozzle expansion ratio
c      ispm :    Isp with mean nozzle expansion ratio
c
c      integer expnu,expnl
c      real etacf,div,kin,bl,tp,sub,eros,astar,s,mf,dp,pc,isps,ispm,ispf,
c      +dt,ispu,isl,erosr
c      common /scratc/ plot(5,100)
c      common /socf/ spi(2),cf(2),oex(2)
c calculate the % of nozzle divergence loss
c      div = 50 * ( 1 - cos ((alpha + thetaex) / 2 ))
c ispf is the frozen and isps is the shifting specific impulse from
c micropep run at nominal pc
c Transfer specific impulse data from MICROPEP.
c      ispf=spi(1)
c      isps=spi(2)
c Calculate the kinetic loss
c      kin = 33.3 * (1 - ispf/isps)
c calculate % boundary layer loss
c Steel nozzle (1), Ordinary nozzle (0). Enter 0 or
c      if (nozzle.eq.1) then
c          c1 = 0.00506
c          c2 = 0.0
c      else
c          c1 = 0.00365
c          c2 = 0.000937
c      endif
c

```



# APPENDIX

```

c expansion ratio of the nozzle for shifting equilibrium from
c micropep with exit pressure=ambient pressure at design altitude
c read (*,70)expn
  expn=oex(2)
  pi=3.14159
  dt=sqrt(ath/pi)*2
  bl=(c1*pc**0.8/(dt*0.2))*(1+2*exp(-c2*pc**0.8*tb/(dt*0.2)))*(1+0.
$016*(expn-9.0))
c calculate the two-phase flow loss
c the mole fraction of condensed phase is come from "MICROPEP"
c mean particle diameter calculation by using empirical relation
  dp = 3.39*dt**0.4692
  if (mf.lt.0.09) then
    mf = 0.09
  endif
  if(dt.lt.1.0) then
    c3=9.0
    c5=1.0
    c6=1.0
  else
    if(dt.le.2) then
      c3=9.0
      c5=1.0
      c6=0.8
    else
      if(dp.lt.4) then
        c3=13.4
        c5=0.8
        c6=0.8
      else
        if(dp.le.8) then
          c3=10.2
          c5=0.8
          c6=0.4
        else
          c3=7.58
          c5=0.8
          c6=0.33
        endif
      endif
    endif
  endif
  c4=0.5
  tp=c3*mf**c4*dp**c5/(pc**0.15*expn**0.08*dt**c6)
c calculate the submergence loss(NOT USED IN PRELIMINARY WORK !!)
c the nozzle is assumed to be of external design with no submergence
c loss. s=length of submergence / length of internal motor.
c  astar=(pi*d**2/4)/ath
c  sub=0.0684*(pc*expn/astar)**0.8*s**0.4/dt**0.2
c  default to 0.0
  sub=0.0
c calculate the nozzle erosion loss
c calculate the ispm (specific impulse at mean expansion ratio)
  df=dt+erosr*tb*2
  dbar=(dt+df)/2
  expnm=(dt**2/dbar**2)*expn
  expnl=int(expnm)
c Transfer expansion ratio of nozzle and specific impulse from MICROPEP.
  ispl=plot(4,expnl)
  expnu=int(expnm)+1

```



# APPENDIX

```

        ispu=plot(4,expnu)
        ispm=(expnm-expnl)/(expnu-expnl)*(ispu-ispl)+ispl
.c erosion loss calculation
        eros=(1-ispm/isps)*100
        write(*,100)div
100 format(1x,'PERCENT DIVERGENCE LOSS..... ',f6.3)
        write(*,110)tp
110 format(1x,'PERCENT TWO PHASE FLOW LOSS..... ',f6.3)
        write(*,120)bl
120 format(1x,'PERCENT BOUNDARY LAYER LOSS..... ',f6.3)
        write(*,130)kin
130 format(1x,'PERCENT KINETIC LOSS..... ',f6.3)
        write(*,140)sub
140 format(1x,'PERCENT SUBMERGENCE LOSS..... ',f6.3)
        write(*,150)eros
150 format(1x,'PERCENT EROSION LOSS..... ',f6.3)
        etacf=1-(div+tp+bl+kin+sub+eros)/100.0
        write(*,160)etacf
160 format(1x,'THRUST COEFFICIENT EFFICIENCY..... ',f6.3)
        return
        end

```

# APPENDIX

```

      subroutine input2(pfac,aport,web,rr5,lgrain,tb,xx)
c*****
c.
c      THE PRIMARY PURPOSE OF THIS SUBROUTINE IS TO ES-
c      TABLISH THE DATA FILE FOR THE CSD "GRAINS" PROGRAM
c
c*****
      character*80 tape5
      character*1 yes
      real lgrain,lspoke,kspoke,RR5
      integer nmax,nspoke,ibb,iprnt
      write(*,*)'The following will be the data input for '
      write(*,*)'spoked star grain designs with radial sides '
      open(4,file='grainin.dat',status='unknown')
      write(*,*)'Run DESIGN-1 mode or BURNBACK-0? Type 1 or 0... '
      read(*,*)i
      if(i.eq.1)then
11        write(*,40)web
14        r=web/tb
          pfac=xx/r
          write(*,13)r
13        format(1x,'Required burning rate, IN/SEC..... ',f12.3)
          write(*,50)pfac
          write(*,*)'Do you want to change the web?...y/n..... '
          read(*,5)yes
          if(yes.eq.'Y'.or.yes.eq.'y')then
            write(*,*)'Input the required web, IN..... '
            read(*,*)web
            go to 14
          endif
          write(*,*)'Max number of spokes?.(I3)..... '
          read(*,*)nmax
          write(*,*)'Initial number of spokes?.(I3)..... '
          read(*,*)nspoke
          ibb=1
          iprnt=0
          write(4,10)nmax,nspoke,ibb,iprnt
          write(*,30)aport
30        format(1x,'Required port area, SQ IN..... ',f12
          *.3)
          write(*,40)web
40        format(1x,'Initial web thickness in IN..... ',f12
          *.3)
          write(*,50)pfac
50        format(1x,'Required perimeter factor ..... ',f12
          *.3)
          write(*,*)'Input Kspoke - Abstract multiplier on '
          write(*,*)'PHI2 - if KSPOKE=0.0 PHI2=0.0 where:'
          write(*,*)'PHI2=ATAN(KSPOKE*WEB/RR3/COS(PHI3)) (0.0-1.0).... '
          read(*,*)kspoke
          write(*,60)rr5
60        format(1x,'Grain outer radius, INCHES..... ',f12
          *.3)
          write(4,20)aport,web,pfac,kspoke,rr5
          write(*,*)'Input initial grain inner radius, INCHES (F7.3) '
          read(*,*)ril
          write(*,*)'Input initial value of SR1 - spoke'
          write(*,*)'top corner radius in IN (Default=0.25)..... '
          read(*,*)sril
          write(*,*)'Input initial value of SR2 - spoke'

```

# APPENDIX

```

write(*,*)'base coner radius in IN (Default=0.25)..... '
read(*,*)sri2
write(4,20)ril,sril,sri2
write(*,*)'Input increment on SR1 in IN - cannot be 0.0... '
read(*,*)del1
write(*,*)'Input increment on RR1 in IN - negative value.. '
read(*,*)del2
write(*,*)'Input increment on NSPOKE Default = 1.0..... '
read(*,*)del3
write(*,*)'Input increment on SR2 in IN - cannot be 0.0... '
read(*,*)del4
write(4,20)del1,del2,del3,del4
write(*,*)'Input tolerance on grain angle sum total - %'
write(*,*)'of 360.(0.0-1.0)..... '
read(*,*)cirtol
write(*,*)'Input tolerance on port area - % of Aport '
write(*,*)'(0.0-1.0)..... '
read(*,*)pttol
write(*,*)'Input tolerance on perimeter - % of perimeter.. '
write(*,*)'(0.0-1.0)..... '
read(*,*)pertol
write(4,20)cirtol,pttol,pertol
write(*,*)'Input Max of SR1 in IN .(F10.5)..... '
read(*,*)fin1
write(*,*)'Input Min of RR1 in IN .(F10.5)..... '
read(*,*)fin2
write(*,*)'Input Max of SR2 in IN .(F10.5)..... '
read(*,*)fin4
write(*,*)'Input Max of web in IN .(F10.5)..... '
read(*,*)finweb
write(*,*)'Input increment for web in IN.(F10.5)..... '
read(*,*)webstp
write(4,20)fin1,fin2,fin4,finweb,webstp
else
  nmax=0
  write(*,*)'Number of spokes?...(I3)..... '
  read(*,*)nspoke
  ibb=-1
  write(*,*)'Do you want optional output? y=yes, n=no..... '
  read(*,5)yes
  if(yes.eq.'Y'.or.yes.eq.'y')then
    iprnt=-1
  else
    iprnt=0
  endif
  write(4,10)nmax,nspoke,ibb,iprnt
  write(*,70)
70  format(1x,'Input initial port area, SQ IN..(F10.5)..... ')
  read(*,*)aport
  write(*,80)
80  format(1x,'Input initial web thickness, IN.(F10.5)..... ')
  read(*,*)web
  write(*,90)
90  format(1x,'Input the perimeter factor..(F10.5)..... ')
  read(*,*)pfac
  kspoke=0.0
  write(*,60)rr5
  write(4,20)aport,web,pfac,kspoke,rr5
  write(*,*)'Input initial RR1, INCHES.(F10.5)..... '
  read(*,*)ril

```

# APPENDIX

```

write(*,*)'Input initial value of SR1 (Default=0.25 IN.).... '
read(*,*)sr1l
write(*,*)'Input initial value of SR2 (Default=0.25 IN.)..... '
read(*,*)sr12
write(4,20)sr1l,sr1l,sr12
del1=0.0
del2=0.0
del3=0.0
del4=0.0
write(4,20)del1,del2,del3,del4
cirtol=0.0
pttol=0.0
pertol=0.0
write(4,20)cirtol,pttol,pertol
fin1=0.0
fin2=0.0
fin4=0.0
finweb=0.0
webstp=0.0
write(4,20)fin1,fin2,fin4,finweb,webstp
write(*,*)'Input grain length, INCHES (F10.5)..... '
read(*,*)lgrain
write(*,*)'Input initial PHI2, DEGREES (F10.5)..... '
read(*,*)dphi2
write(*,*)'Input initial PHI4, DEGREES (F10.5)..... '
read(*,*)dphi4
write(4,20)lgrain,dphi2,dphi4
write(*,*)'Input # of steps in decimal format'
write(*,*)'Input # of burnback steps for SR1>0..... '
read(*,*)step1
write(*,*)'Input # of burnback steps for PHI2>0 & SR1=0.... '
read(*,*)step2
write(*,*)'Input # of burnback steps for LSPOKE=0 & PHI2>0. '
read(*,*)step3
write(*,*)'Input # of burnback steps for '
write(*,*)'triangular spoke burnback..... '
read(*,*)step4
write(*,*)'Input # of burnback steps for '
write(*,*)'remaining fuel burnout..... '
read(*,*)step5
write(4,20)step1,step2,step3,step4,step5
endif
5  format(a1)
10 format(4i3)
20 format(5f10.5)
close(4,status='keep')
return
end

```



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